RADIOACTIVITY WELL LOGGING
EDMONTON DISTRICT
ALBERTA

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The undersigned hereby certify that they have read and recommend to the School of Graduate Studies for acceptance, a thesis entitled, "Radioactivity Well Logging, Edmonton District, Alberta," submitted by Edward Wallace Jennings, B.Sc., in partial fulfilment of the requirements for the degree of Master of Science.

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THE UNIVERSITY OF ALBERTA

RADIOACTIVITY WELL LOGGING
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A DISSERTATION

SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF MASTER OF SCIENCE

FACULTY OF ARTS AND SCIENCE

DEPARTMENT OF GEOLOGY

by

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ABSTRACT

Radioactivity well logging, one of the newest processes for subsurface investigation, has proven to be of great value in correlation work and other stratigraphic studies. This thesis embodies work on three separate phases of the process.

The high degree of radioactivity exhibited by the First White Speck zone, marking the top of the Colorado formation, has been investigated by means of Geiger Counter studies of powdered samples. No abnormally high radiations have been noted in the light, heavy, or bulk fractions of the samples, using apparatus available in the Department of Physics. The counter, however, was not sufficiently shielded from cosmic ray background to measure the low intensity of sedimentary radiation. Petrographic study of the samples shows three possible sources of radioactivity - bitumen, biotite and glauconite.

The gamma ray log and electrical potential log are both found to exhibit some errors in determining formation contacts. It is the writer's opinion that the gamma ray log is the more accurate of the two. A constant pattern of deviations in determining the tops of the

horizons studied between the gamma ray log and electrical potential log is noted, and it is suggested that this pattern may be used in the derivation and application of corrections to the logs.

Gamma ray logs may be used in short and long range correlation work within and between oil fields. A high definition of strata exists in the logs and enables the observer to trace lithologic changes within a formation, if sufficient numbers of logs are available. The logs may also be used as an aid in studying facies changes in the sedimentation of an area.

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GENERAL INTRODUCTION

The discovery of large petroleum reservoirs under the plains of central Alberta in 1947 and 1948 tremendously stimulated the search for oil in this province. Large programs of exploration have been undertaken by many oil companies, and the development of proven reserves has kept pace with the exploration. One of the results of this surge of activity has been the expansion and development of older methods of subsurface investigation, and a great influx of new methods. One of the most promising of the new tools of subsurface study is the radioactivity well log.

Since its introduction in 1940 radioactivity well logging has been gaining steadily in popularity in the petroleum industry of the United States. The process was first used in Canada in August, 1949. Because of the newness of the process, geologists are not as well acquainted with it as with older methods. Great strides are being made in the study, however, and it is now used extensively in stratigraphic correlation work, and in porosity studies in such oil fields as Redwater.

Purpose of Thesis

The purpose of this thesis is threefold:

1. To study a phenomenon discovered when radioactivity surveys were first made in Alberta, which is the apparently large radioactive intensity manifest in the First White Speckled Shale zone of the Colorado formation.
2. In a selected area, the Redwater Oil Field, to compare the relative accuracies of radioactivity logs and electric logs,(another form of well logging), in selecting formation contacts to a standard which is taken as being accurate.
3. To show an application of the radioactivity log as a means of short range correlation within a single field, and as a means of long range co-rrelation between two fields. The value of the radioactivity log as a lithologic indicator is also discussed.

Some mention is also made of another commercial application of the radioactivity log, the evaluation of reservoir rock porosity.

Acknowledgments

The writer wishes to express his appreciation for the assistance given him by various oil and service companies. Radioactivity and electric

logs were generously supplied by Imperial Oil Limited, Royalite Oil Company Limited, British American Oil Company Limited, Home Oil Company Limited, and Pacific Petroleums Limited. Cores and samples of the First White Speckled Shale zone were given by Imperial Oil Limited.

Mr. W.B. Gallup of Royalite Oil Company, Mr. C.F. Ludwig and Mr. W. Kennedy of Lane-Wells Company, and Mr. J. Sparks of Halliburton Oil Well Cementing Company gave the writer much valuable data and reference material unobtainable elsewhere.

Dr. W.W. Happ, Mr. A.J. Goodjohn and Mr. T. Wilson of the Physics Department, University of Alberta, assisted the writer, providing the Geiger counter and other equipment for Part One of this work.

The writer also wishes to thank the members of the Department of Geology, University of Alberta for their assistance, especially Dr. R.E. Folinsbee under whose direct supervision this thesis was written.

Finally, to my wife Laverna who typed and proof read the thesis, I express my deep gratitude.

A STUDY OF THE RADIOACTIVITY OF THE FIRST WHITE SPECKLED SHALE ZONE OF THE COLORADO FORMATION

Introduction

In the past half century the radioactivity of rocks has been the subject of many investigations, the results of which have contributed much to the solution of geological problems, Most of these studies, prior to 1940, have been on igneous rocks, and before 1933 the measurements were, as a rule, inaccurate due to lack of precision in standards (10,12).* Since 1933, when modern techniques and apparatus were developed for measuring the radioactivity of igneous rocks, many investigators have made laboratory analyses of these rocks.

The advent of radioactivity well logging in 1939, a process which rapidly established itself as a standard means of oil field investigation, made apparent the need for sedimentary radioactivity studies. Russell (9,10,11), Evans and Goodman (2), Bell, Goodman and Whitehead (1), and others have pioneered this work, and their results have been used as the basis for present day work.

* Figures in brackets refer to Bibliography.

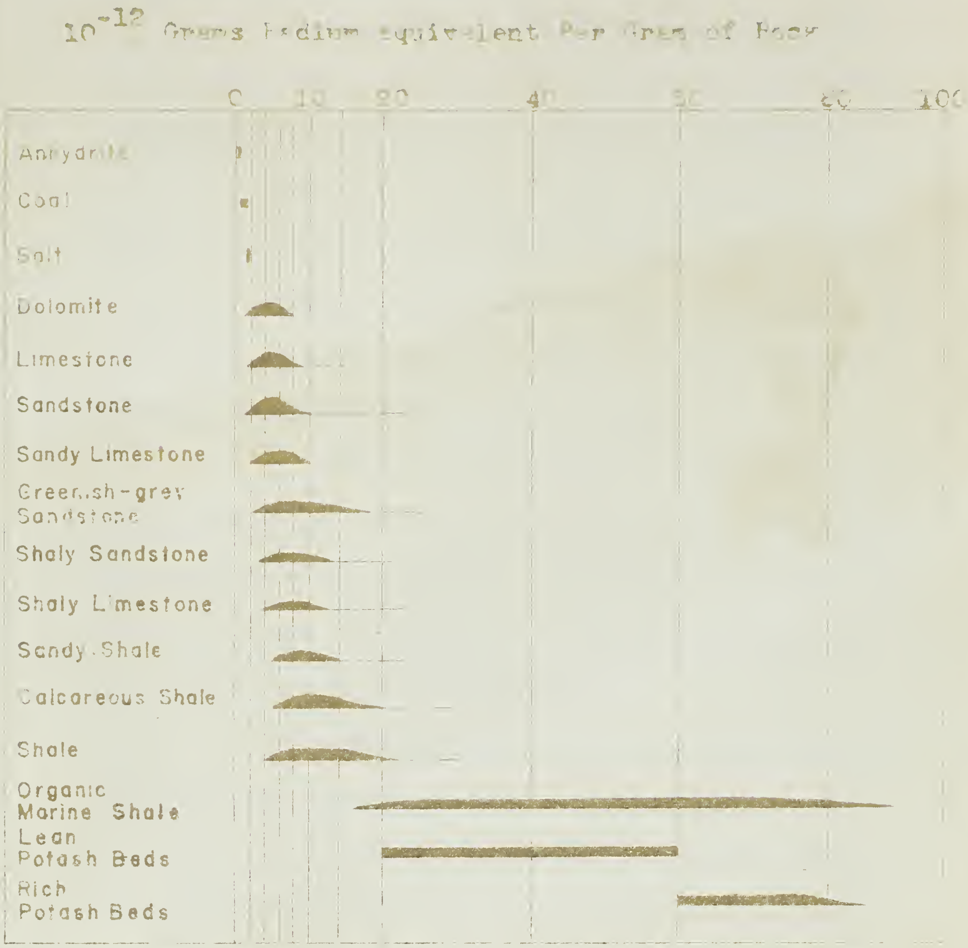


Figure 1-2. Diagram showing the relative radioactivities of various sedimentary rocks as indicated by their gamma ray intensities. Vertical width of line increases with frequency of occurrence. After W.L. Russell (6).

(Referred to in text as Table 1-1)

Radioactivity of Sediments

It has been found that all rocks contain measureable amounts of radioactive material, although it is generally present in extremely minute quantities. Most of the radioactive elements belong to one of three series, the uranium, actino-uranium, or thorium series. Potassium is also radioactive, but it forms no series as its product undergoes no further change.

A detailed discussion of the process of disintegration of radioactive material is beyond the scope of this thesis. The reader interested in this phase is referred to the literature at the end of part one (3,12,13,14).

W.L. Russell has given us comprehensive information on sedimentary radioactivity. His analyses of the total gamma ray content of sediments by means of the Geiger Counter (10) has made possible the grouping of these sediments according to their relative radioactivities. This is shown in Table 1-1.

The cause of sedimentary radioactivity has been explained chiefly by the presence of uranium-radium and thorium salts. Some authors favor the hypothesis that heavy minerals are re-

sponsible, but most ~~say~~ contend that the salts of these elements precipitate in conditions favoring the accumulation of certain types of sediments such as oil shales (11). Tiratsoo (13) recently has advanced the theory that it is not the uranium-thorium series members which are responsible for sedimentary radioactivity. In his opinion the radioactive isotope of potassium, K^{40}, is chiefly responsible for the phenomena observed in sediments. His evidence for this is shown in chemical analyses of typical limestones, sandstones and shales. These analyses show that the potassium proportion in the three rock types is 1:3.8:8.6. These ratios are of the same order as the ratios of radioactivity, measured in terms of grams x 10^{-6} of radium per gram of rock, which have been obtained by Russell and others. Tiratsoo believes that glauconite is one of the chief factors in concentrating potassium in sediments. He states that analyses show that glauconite contains about 5% potassium, hence a bed with 25% glauconite would be composed of 1.25% potassium. Although the radioactive component forms only 0.011% of the total potassium content, it would form a much greater part of a sediment than any other radioactive element.

Present Work

The top of the Colorado shale in Alberta, and elsewhere, is marked by the occurrence of a zone of white, calcareous specks. This zone varies slightly in thickness between 50 and 100 feet, but is a very constant horizon over the whole of the western plains. The "White Specks", as the zone is called, forms an excellent marker horizon widely used in drilling oil wells.

When radioactivity surveys are run through the White Speck zone it is found that it exhibits a high degree of radioactivity, far above normal for the marine shales of the area. (Figure 1-1). This is rather peculiar because calcite, with the exception of a few limestones, is noticeably low on the radioactivity scale. (Table 1-1). The present work is an attempt to explain this apparent anomaly, and to determine if possible, the source of the radioactivity exhibited.

Unfortunately the writer was not able to obtain samples of cores or bit cuttings from a well on which a radioactivity survey had been run. However, as the zone exhibits abnormal, though erratic, radioactivity in all the logs the writer has in his possession, any samples

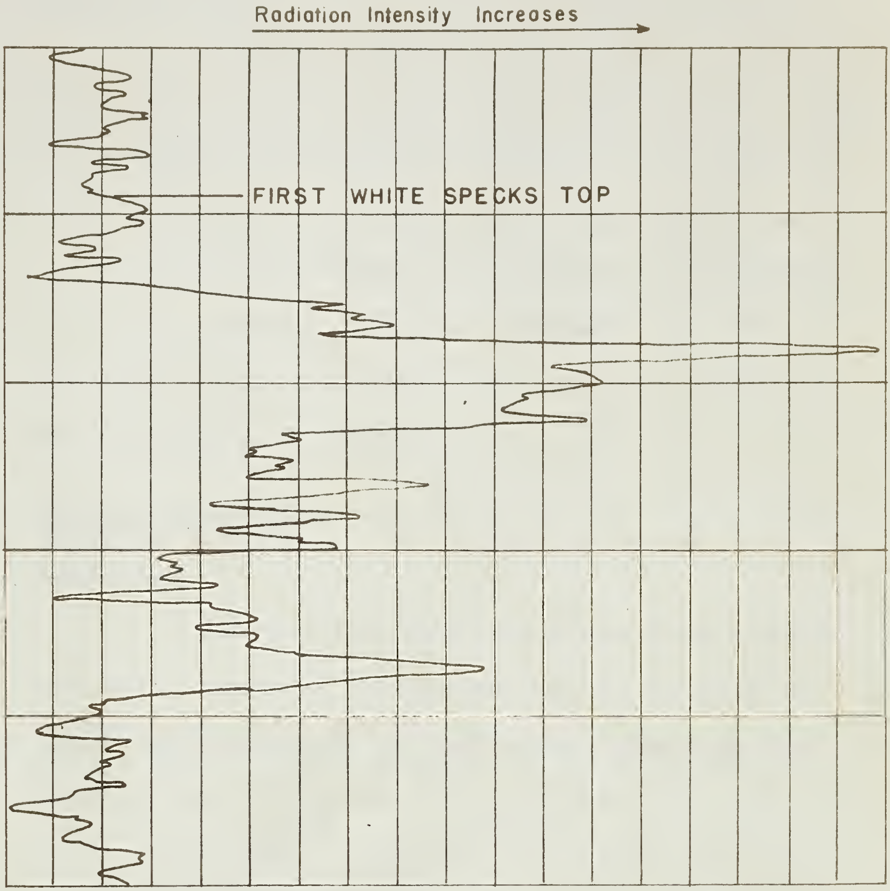


Figure 1-1. An example of the gamma-ray log of the First White Speckled Shale zone in the Redwater area. The typical marine shale base line for the area is shown in the bottom 50 feet. Distance between the horizontal lines is 50 feet.

would be expected to be of value in the study.

As just mentioned, the logs of the White Speck zone from different wells show a very erratic distribution of radiation "highs". The peak deflection may be near the top of the zone in one well, toward the middle in another, as in Figure 1-1, and near the bottom of the zone in a third. The writer has no explanation for this variation in radioactivity peaks.

Methods of Study

Sampling:

Samples for this study are from a wildcat well, Imperial Youngstown No. 1, located in Legal Subdivision 5, of Section 3, Township 30, Range 9 West of the fourth Meridian. The First White Speck zone of this well is cored with a 2 inch diameter conventional core bit. The writer was not present when samples of the core were packed, but presumes them to be representative. Unfortunately the complete White Speck zone is not represented in the samples, as samples of core No. 1 are not present, and the base of the zone is not cored.

Cores numbers 2 and 3, covering an interval of 36 feet are represented in the samples.

Three pieces of core per 2 feet 6 inches (approximately) interval are packed.

The writer also has bit cutting samples from two other wells. The sample intervals, however, are erratic, and the samples are badly contaminated with cavings and drilling mud, hence they were not used in this thesis.

Crushing:

A representative powder sample of each sample interval of the cores is obtained in the following manner. A fragment, approximately the same size, of each piece of core per interval is broken off and placed in a mortar. The three pieces are then pulverized together until the resultant powder passes a Tyler Standard 100 mesh screen, (0.15 millimetre opening). This method ensures a uniform mixing of the three fragments' powder, and thus a uniform sample.

Heavy Mineral Separation:

A portion of each powdered sample, enough to fill a 2 gram planchette is used in the heavy mineral separation. Washed bromoform of specific gravity greater than 2.7 (calcite) constitutes the heavy liquid. The technique of separation is that described by Krumbein and Pettijohn (7).

The separated fractions are then tested for their radioactivity.

Radioactivity Measurements:

The radioactivity measurements made by the writer were carried out using a Geiger Mueller counter tube. The tube was enclosed in a box lined with 2 inches of lead. The instrument and counters were built by Mr. A.J. Goodjohn and described by him (4).

Three readings were taken, where possible, on each sample interval, the bulk, heavy and light fractions each being investigated. Enough of the sample under investigation to fill a 2 gram planchette half full, where this was possible, was placed under the tube. The radiations of the sample were then counted for a period of one-half hour. Background counts were taken at the beginning and the end of each period during which several samples may have been measured. It was found that over a period of three or four hours the background did not vary greatly.

Errors:

Errors in the measurements were chiefly confined to statistical fluctuations. Instrumental error occasioned by two superimposed radiations

TABLE 1-2

Sample Number	Sample Type	Net Sample Counts	Sample Number	Sample Type	Net Sample Counts
IY2A	Bulk	3.4 ± 2.2	IY3A	Bulk	1.6 ± 2.2
	Light	4.2 ± 2.2		Light	3.7 ± 2.1
	Heavy	0 ± 2.2		Heavy	2 ± 2.0
IY2B	Bulk	7.7 ± 2.3	IY3B	Bulk	4.6 ± 2.2
	Light	5.1 ± 2.3		Light	2.6 ± 2.2
	Heavy	*		Heavy	2.5 ± 2.3
IY2C	Bulk	4.2 ± 2.3	IY3C	Bulk	4.9 ± 2.3
	Light	6.1 ± 2.3		Light	3.1 ± 2.2
	Heavy	2.2 ± 2.1		Heavy	2.3 ± 2.3
IY2D	Bulk	3.3 ± 2.3	IY3D	Bulk	5.1 ± 2.3
	Light	4.6 ± 2.3		Light	4.6 ± 2.2
	Heavy	3.5 ± 2.4		Heavy	3.5 ± 2.1
IY2E	Bulk	5.9 ± 2.3	IY3E	Bulk	5.7 ± 2.3
	Light	5.9 ± 2.4		Light	3.9 ± 2.2
	Heavy	*		Heavy	*
IY2F	Bulk	5.2 ± 2.3	IY3F	Bulk	4.6 ± 2.3
	Light	5.1 ± 2.2		Light	2.8 ± 2.2
	Heavy	*		Heavy	3.1 ± 2.4
IY2G	Bulk	3.6 ± 2.1	IY3G	Bulk	2 ± 2.0
	Light	0 ± 2		Light	3.5 ± 2.3
	Heavy	4.4 ± 2.1		Heavy	4.3 ± 2.1

Radioactivity Measurements of Sample Fractions using a Geiger Counter.
* indicates sample too small to be analysed.

being counted as one by the instrument were not taken into account because the radiation intensities were so low that this situation was considered practically non-existent. The errors occasioned by the statistical fluctuations were computed by taking the square root of the total number of radiations for the period of time the measurement took. These calculations were made for background and sample measurements. The resultant errors were then divided by the respective time intervals so that the error per minute was obtained in each case. In calculating the net sample counts per minute, the errors of background and sample counts were additive.

Examination of Samples:

The core samples were examined under a binocular microscope for their lithologic character. The description of the samples are contained in Appendix 1-A.

Immersion mounts were made of the heavy and light mineral fractions, and these were examined under a petrographic microscope. In general, the grains were too small for identification, the majority appearing to be opaque. In many samples the heavy mineral fraction amounted to

TABLE 1-3

MINERALS IDENTIFIED IN IMMERSION MOUNTS

Mineral	Freq.	Remarks
		HEAVY FRACTIONS
Biotite	5	Many basal cleavage flakes showing pseudohexagonal shape.
Garnet	2	Red variety, grains rough, angular
Magnetite	3	Worn octahedra and round grains present.
Pyrite	4	Rounded, worn looking grains.
Zircon	1-	Minute, rounded, worn grains.
		LIGHT FRACTIONS
Bitumen	3-4	Opaque black grains, do not appear to be a mineral.
Calcite	4	Small acicular crystals.
Glauconite	1	Green, earthy.
Quartz	3	Minute round and sub round grains.
Ground Mass		Black, opaque, some included pyrite grains.

Frequency Scale:

5 - very abundant
4 - abundant
3 - common
2 - rare
1 - very rare

only a few grains. Table 1-3 shows the minerals identified in the heavy and light fractions, and their relative abundance.

Results

A summary of the radioactivity measurements of the powdered core samples is contained in Table 1-2. The sample reference numbers used represent the core intervals described in Appendix 1-A.

The minerals identified in the petrographic studies of the powdered samples are contained in Table 1-3 along with their relative abundance.

Discussion of Results

The radiation intensities of the samples measured by the Geiger counter are, on the whole, too low to be of any significance. A glance at Table 1-2 will show that in the majority of cases the errors occasioned by the statistical fluctuations are equal to or exceed the net sample counts. The instrument used was designed to measure the radiations of more highly radioactive substances which give thousands of counts per minute. It is therefore not adequately shielded from the cosmic

background for studying sediments whose total counts are of the same order, or less than the background.

Table 1-3 shows several minerals which are possible sources of radioactivity. In the light mineral fraction the substance tentatively identified as bitumen in the petrographic study and also seen in the core samples (Appendix 1-A) could be responsible for the intensities shown on the radioactivity log. Bell, Goodman, and Whitehead (1) report that crude oil samples analysed by them have a great affinity for radon, some samples containing up to 20 times as much absorbed radon as would be expected from the amount of radium in the surrounding beds. Dr. A.J. Goodman * states that photomicrographs of the White Speck zone show streaks of bituminous material. In his opinion the bitumen may explain the radioactivity.

In the heavy mineral fraction of the samples abundant flakes of biotite occur, throughout the section. In some core samples these flakes are so numerous and large that they are visible to the naked eye. (Samples IY2D, IY3D). The writer picked enough of these flakes out of the core to

* Personal communication

cover the bottom of a planchette and attempted to measure their radiation. However the instrument gave very erratic readings and it is suspected that some contaminating material was present. Since biotite consists of 11.2% K_2O, (5), it would be expected to contain a relatively high proportion of the radioactive isotope of potassium. The wide variation of the biotitic phases of the core samples might also account for the fluctuations shown by the gamma ray logs.

A third possible source of radioactivity is glauconite. While it was recognized under the petrographic microscope in one sample only, and in the core samples in rare instances, there is the possibility that it exists in sufficient quantities as it does in the basal Lea Park (8), to affect the total radioactivity of the section.

Conclusions

1. The radioactivity of the First White Speckled shale zone is not sufficient to be studied on the surface by means of a Geiger Counter tube unless special shielding devices are placed about the instrument to eliminate cosmic ray background.

2. There are two and perhaps three possible sources of the radioactivity observed in the zone. These are (a) bitumen, (b) biotite, (c) possibly

glauconite.

It is the writer's opinion that the problem of the source of radioactivity in the White Speck zone merits further study. For this purpose it is suggested that a Geiger counter tube equipped with a sample sleeve similar to that described by Tiratsoo (12) and adequately shielded, be constructed.

While there is no evidence at present that the White Specks, themselves, and the radioactivity of the zone are bound together, it is peculiar that the section of their occurrence is marked by an extreme deflection of the gamma ray curve. Perhaps if the source of the radioactivity of the zone can be determined, the problem of the origin of the specks will have a definite light thrown upon it.

BIBLIOGRAPHY

1. Bell, K., Goodman, C., and Whitehead, W.; (1940): Radioactivity of Sedimentary Rocks and Associated Petroleum; Bull. Amer. Assoc. Pet. Geol., Vol. 24, No. 9.

2. Evans, R., Goodman, C.; (1941): Radioactivity of Rocks; Bull. Geol. Soc. America, Vol. 5

3. Fearon, R.E.; (1945): Radioactivity Well Logging; The Oil Weekly, June and July.

4. Goodjohn, A.J.; (1951): A Study of the Half-Life and Decay Energies of Rubidium ^{86}; Unpublished M.Sc. thesis; U. of A.

5. Grout, F.F.; (1932): Petrography and Petrology, New York, McGraw Hill Book Co.

6. Henderson, G.H. and Bateson, S.; (1934): A Quantitative Study of Pleochroic Haloes; Proc. Roy. Soc., Pt. A, Vol. 145.

7. Krumbein, W.C. and Pettijohn, F.J.; (1938): Manual of Sedimentary Petrography; New York, D. Appleton-Century Co.

8. Nauss, A.W.; (1945): Cretaceous Stratigraphy of Vermilion Area, Alberta, Canada; Bull. Amer. Assoc. Pet. Geol., Vol. 29, No. 11.

9. Russell, W.L.; (1941): Well Logging by Radioactivity; Bull. Amer. Assoc. Pet. Geol. Vol. 25, No. 9.

10. -------------; (1944): The Total Gamma Ray Activity of Sedimentary Rocks as Indicated by Geiger Counter Determinations; Geophysics, Vol. 9, No.2.

11. -------------; (1945): Relation of Radioactivity, Organic Content and Sedimentation; Bull. Amer. Assoc. Pet. Geol., Vol. 29, No. 19.

12. Tiratsoo, E.N.; (1949): The Radioactivity of Sediments, Part 1; Petroleum, March.

13. ---------------; (1949): The Radioactivity of Sediments, Part 2; Petroleum, May.

14. ---------------; (1949): The Radioactivity of Sediments, Part 3; Petroleum, July.

15. ---------------; (1949): The Radioactivity of Sediments, Part 4, Petroleum, Dec.

APPENDIX 1-A

LITHOLOGIC DESCRIPTION OF CORE SAMPLES

WELL: Imperial Youngstown No.1
Top of First White Specks: 1760 (+815)

Core #2	1820 - 1838'	Recovery 18'

0-2'8"
IY2A
: Shale, medium grey, calcareous, micro-micaceous, fissile; scattered thin, transparent biotite flecks up to 2mm. in diameter lying parallel to bedding planes; occasional fossil fragment and carbonized plant fragments; scattered traces of glauconite(?) throughout shale and associated with white specks. Traces of bitumen.
Abundant white, calcareous, structureless specks. These are apparently very thin and lie parallel to bedding planes.

2'8"-5'4"
IY2B
: Shale, medium grey, calcareous, scattered, small nodules throughout samples (collophane spheres?). Traces of columnar aragonite from decomposing shells. Less glauconite than above. White specks not so abundant as above.

5'4"-8'
IY2C
: Shale, medium grey, calcareous; traces of flaky biotite as above; scattered groups of small nodules; traces of fossil fragments. (Inoceramus?)
White specks concentrated in small groups in these samples, not very abundant.

8'-10'8"
IY2D
: Shale, medium and light grey, small silty phases. One sample contains very thin biotite flakes up to 1 mm. in diameter. Scattered fossil (Inoceramus?) fragments, carbonized plant remains, and fish scales. Some small brown spheres (collophane?). Some bituminous particles.
White specks variable, being plentiful in one sample, confined to a small group in the second, and scattered in the third. The specks in this last sample are also smaller - about 1 mm. in diam.

10'8"-13'4" IY2E	:	Shale, medium grey to slightly greenish (glauconite?); scattered flakes of finely divided biotite; traces of fossil shell fragments (Inoceramus?) carbonized plant remains and fish bones(?) and teeth. One sample shows slight slickensiding on a fracture plane. Traces of bitumen. White specks variable; in one sample they are confined to a small group approximately 2x10 mm., with the rest barren, in other samples they are scattered throughout.
13'4"-16' IY2F	:	Shale, grey, calcareous, traces small calcareous, silty phases; some small scattered biotite flakes; some fossil shell fragments, plant remains and fish teeth and scales. Some bitumen. White specks medium to abundant. In one sample the specks look different, being long (5 mm.) and thin ($\frac{1}{2}$ mm.), and wavy. This is in a fossiliferous fragment and the specks look like remains of shells and not typical.
16'-18' IY2G	:	Shale, grey and light grey, slightly silty in part; trace to abundant fine biotite flakes; scattered fossil (Inoceramus) shell fragments, fish scales and bones. White specks variable; one sample contains abundant specks in small groups; the second has them scattered widely, the third has few specks.

General Observations

1. Specks appear to be in groups, although this is not general.

2. Silty phases are barren of specks.

3. Specks appear to be structureless except in one sample (13'4"-16').

4. Some disintegrating shells show columnar aragonite

others none, but in all cases the shells were distinct from the specks.

5. Small spheres are scattered throughout (collophane).

6. Some glauconite is associated with specks and, in places, is scattered through shale.

7. Shale appears to be very thin alternating layers of mudstone and calcareous material. In acid, the calcareous material dissolves leaving thin flakes of mudstone. This may account for fissility of shale.

Core #3	1838-1856'	Recovery 18'
0-2'8" IY3A	: Shale, medium grey, calcareous; traces of biotite; traces of fossil fragments and fish scales. White specks abundant, scattered throughout core in two pieces; tending to group in third piece. Specks up to 1 mm. in diameter.	
2'8"-5'4" IY3B	: Shale, medium grey, calcareous, silty in part; traces to scattered biotite flakes; some fossil fragments. Traces of bitumen(?). White specks variable; from rare to plentiful, scattered to groups. Some specks are buff colored. There are no specks in silty portions of core.	
5'4"-8' IY3C	: Shale, medium grey, calcareous, several silty phases, traces glauconite(?); traces biotite to abundant in one piece of core. White specks variable although generally scattered throughout core. One group arranged symmetrically, however no fossil evidence is found. Another group is among fossil fragments. These specks are aragonite crystals, however they are very different from typical white specks.	

8'-10'8" IY3D	: Shale, dark grey, calcareous, silty in part, one fragment having a biotitic siltstone phase and traces of biotite throughout; traces fossil fragments, some with columnar aragonite layers. Traces of bitumen. White specks are rare or sparsely scattered, they are noticeably absent from the siltstone phase although they are present around it and approach the edge of the silt.
10'8"-13'4" IY3E	: Shale, dark grey, calcareous, silty to slightly silty;traces of plant fragments. White specks almost absent from interval, one piece carrying traces.
13'4"-16' IY3F	: Shale, dark grey, calcareous, scattered flakes of biotite, some collophane(?) spheres; traces plant remains and fish scales; some fossil fragments. Some bitumen. White specks scattered and not abundant.
16'-18' IY3G	: Shale, dark to medium grey, calcareous, traces of biotite flakes; a few fossil fragments (Inoceramus?). White specks abundant to rare - occur in groups.

General Observations

The most noticeable feature is the complete absence of any specks from the silty phases of the core. There are a few traces of bitumen or carbonized plant fragments in the cores.

PART TWO

COMPARATIVE STUDY OF THE RADIOACTIVITY AND ELECTRIC LOGS FOR CERTAIN FORMATIONS OF THE REDWATER OIL FIELD

Introduction

Although much has been written on the theories, procedures, and practical applications of radioactivity and electric well logging, few papers have actually compared or contrasted the two methods (3,9,10)*, and fewer still, beyond pointing out a similarity in the profiles of the curves, have attempted a correlation between the curves, or a study of the possible errors in determining the tops of formations from the logs. G.F. Shepherd (13) has shown the correlation of horizons on the two types of logs relative to the bottom of the drill hole, for use in selecting suitable locations for perforating casing.

Scope of Work

The writer has attempted in this paper to establish a correlation between radioactivity logs, electric logs, and the accepted depths of formations. This has been done by a comparative study of the gamma ray curve of the radioactivity

* Figures in brackets refer to bibliography

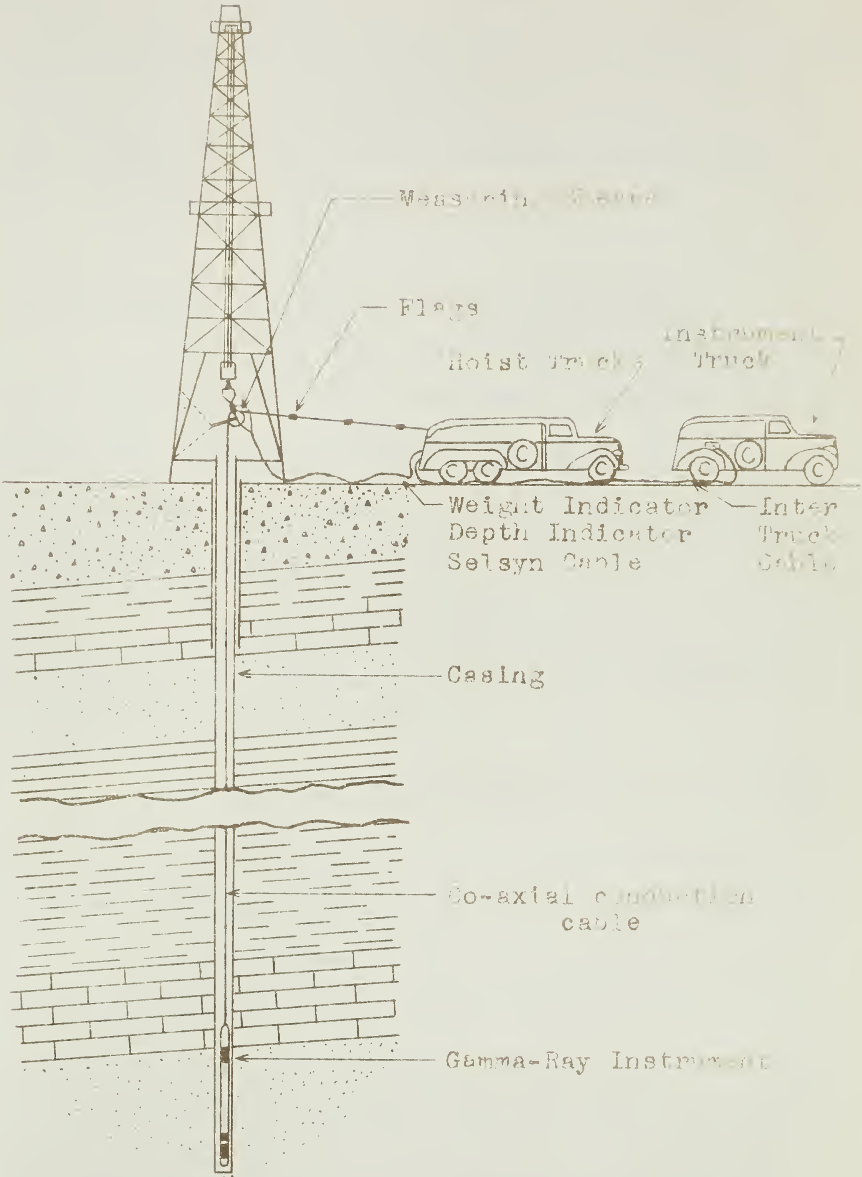


Figure [illegible]-1. Typical set-up for Radioacti[illegible] Well Logging operations. (From Lane [illegible] Bulletin RA-47-B-1)

log and the potential curve of the electric log for four formations in the Redwater Oil Field, and their respective relations to the depths of these formations as published in the Schedule of Wells and Weekly Reports of the Petroleum and Natural Gas Conservation Board.

Well Logging and Well Logging Instruments

In order that the reader may appreciate more fully the information contained in the two types of well logs, a brief description of the instruments and methods used in logging follows.

Radioactivity Well Logging:

A typical set-up at the well head for carrying out a radioactivity survey is shown in Figure 2-1.

For the purpose of this thesis, a radioactivity log is considered to be the gamma ray, or natural radioactivity curve only, and the neutron or artificially induced radioactivity curve is not discussed except briefly in a later section. The instruments in the following descriptions are used in obtaining the gamma ray curve, although they are also applicable to the neutron curve almost in their entirety.

Instrumentation:

The essential instrument in the well

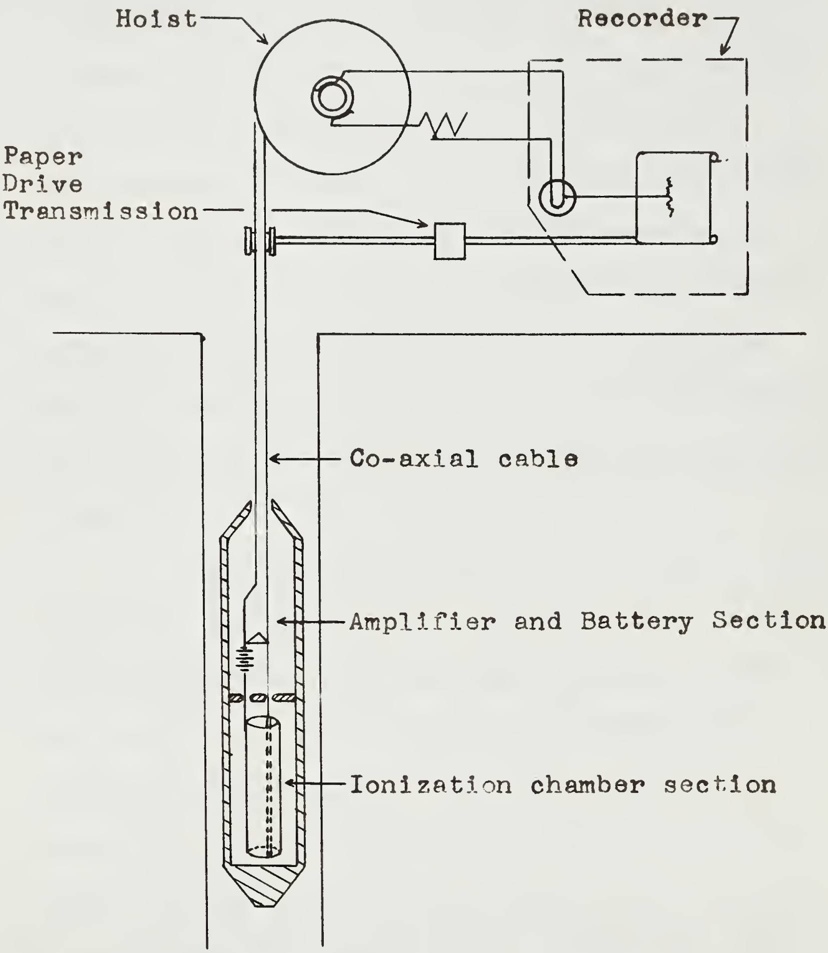


Figure 2-2. Schematic diagram of ionization chamber and associated instruments. After R.E. Bush (1)

logging apparatus is the ionization chamber and its associated batteries and amplifiers. (Figure 2-2). These are contained in a heavy metal cylinder 10 feet 8 inches long and approximately 3 5/8 inches in diameter. The walls of this cylinder are necessarily thick to withstand any pressure which might be met in a bore hole. Instruments in use at the present time will withstand a maximum pressure of 12,500 pounds per square inch. The thick walls also serve another purpose in that they allow only the most penetrating radiations to enter the ionization chamber; thus they act as a selective filter in the logging of the well.

The ionization chamber, located in the bottom of the cylinder, is 3 feet long. It is filled with 99.9 per cent pure argon gas under high pressure. Two insulated electrodes are imbedded in the chamber and are connected to batteries contained in another part of the cylinder. Under normal conditions no current will flow through the argon when an electrical potential is placed on the electrodes. When the chamber is exposed to gamma rays, however, the gas becomes partially ionized and permits the flow of the current. It should be noted that it

is not the radiations themselves which cause the current, they only ionize the gas.

Radioactive minerals form only an extremely small part of the sediments and their gamma radiations, which affect the ionization chamber, are proportionately small in number. Hence only a very small current flows between the electrodes. The intensity of this current varies directly as the ionization of the gas in the chamber which, in turn is proportional to the intensity of the gamma ray bombardment.

The variations in the current passing through the ionization chamber are also extremely small, about one ten trillionth of an ampere. Amplifiers in the body of the bore hole instrument amplify these variations immensely. They are then sent up to the surface through a co-axial cable. This same cable is used to raise and lower the instrument in the hole.

The instrument truck, to which the amplified current variations are sent, contains further amplifiers, a sensitivity control, time constant control, and an automatic pen recorder which produces a log of the variations on a moving roll of paper.

The sensitivity control sets the horizontal deflection of the pen recorder for a given radiation intensity. It is usually set before the instrument is lowered into the bore hole although the operator may change the setting while logging is in progress. To set the control a reference bottle containing a gamma ray source of known intensity is placed next to the ionization chamber and the deflection of the pen recorder for this bottle is noted and set for the conditions likely to be encountered in the hole. If the section to be logged is weakly radioactive, or if the contrasts in the radioactivity of the strata are slight, the sensitivity of the instrument is increased. Conversely, if the section is strongly radioactive, the sensitivity is reduced. The reference line is always placed at the top of the log, an arrow with a figure indicating the deflection in inches.

The intensity of the gamma rays affecting the instrument at any given depth in a well is not constant, but fluctuates due to the chance disintegrations of the radioactive substances. If these variations are measured over a very short time interval they will be very large. However, as the time interval is increased the variations will become progressively smaller, tending to

approach a fixed average.

If the pen of the automatic recorder were allowed to respond to each variation in radiation intensity it would record a rapid succession of peaks and lows which would have no marked relation to the over all radioactivity of the formation surveyed. This effect is eliminated by a device called the time constant control which averages the variations over a suitable time interval. The proper setting of the control depends principally on the speed at which the logging is done, and to a degree, on the sensitivity used. If a section is surveyed at 22 feet per minute (the normal logging speed in Alberta), the ionization chamber would be affected by a thin stratum for about 10 seconds, and the time constant control would be set to average the variations over this period. If the logging speed were reduced to 11 feet per minute, the averaging period would be twice as long. The log produced is a smoother curve, reflecting the characteristic radioactivity of a formation rather than the individual variations for thin strata. The time constant control in use at the present time is pre-set before the instrument is taken into the field.

The log produced is recorded on a continuous roll of logging paper synchronized to

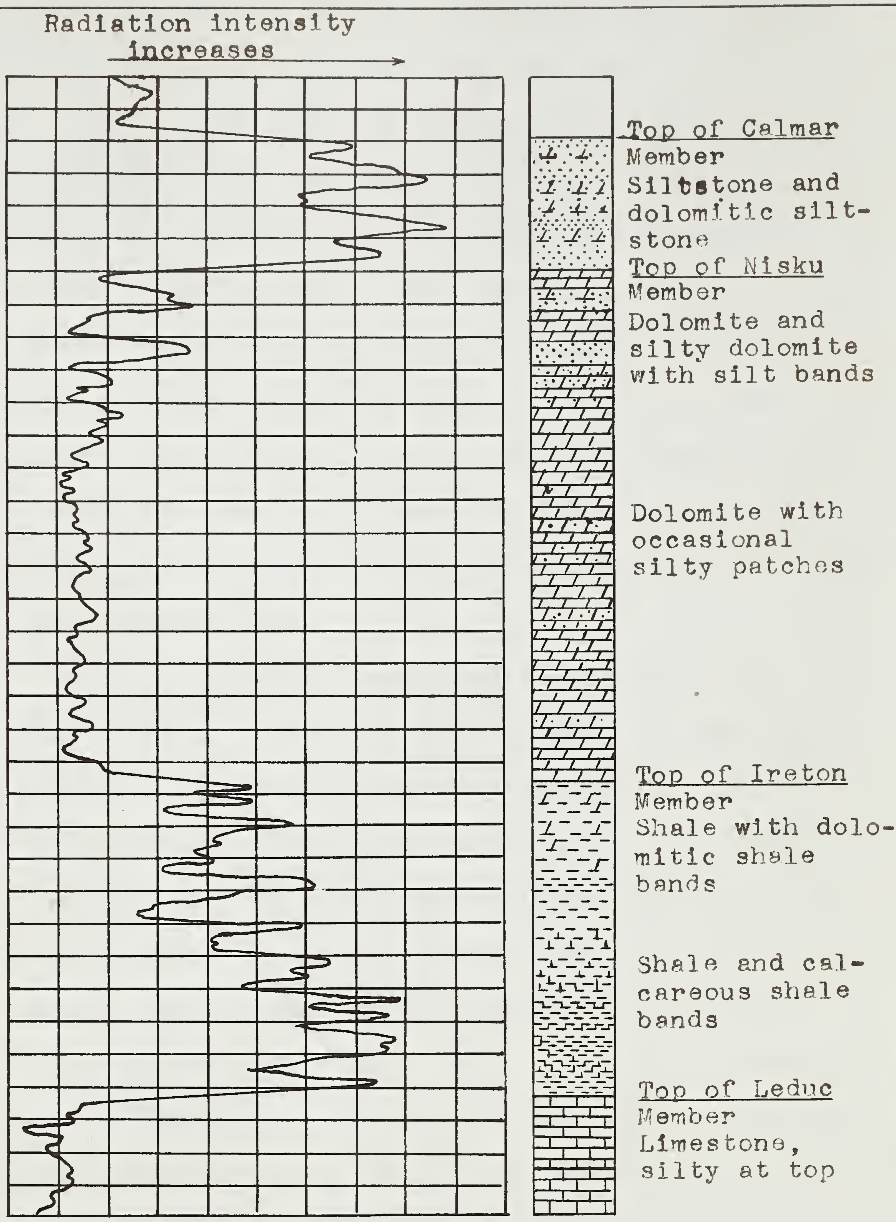


Figure 2-3. Typical gamma-ray log of four Devonian formations. Geologic column at right shows log interpretation of lithology. (Imperial Opal No. 9)

the movement of the bore hole instrument by means of a transmission drive from the hoist truck.

The depth of the instrument in the hole is calculated ~~measured~~ by the measuring sheave, centered over the well opening, and is indicated electrically on an odometer dial in the instrument truck. The measuring sheave has a self contained adjustment feature which compensates for the wear of the sheave rim and the cable. A further check on the depth accuracy is available by means of metal flags set at known intervals along the length of the cable.

The Gamma Ray Log:

A typical gamma ray log is shown in Figure 2-3. It will be noticed that no definite values of radiation intensity are given. This is because the log is qualitative rather than quantitative. If one knows the radiation intensity of the reference bottle which produced the deflection shown, then a quantitative measure of the radioactivity could be made. This information, however, is confidential at the present time and has not yet been released by Lane Wells Co. Ltd.

Electric Well Logging:

Earth potentials were observed for the first time more than one hundred years ago by the Englishman R.W. Fox who made potential measurements in a mine shaft in Cornwall (3). Since the

beginning of the twentieth century this phenomenon has been used extensively in surface exploration and mining, and applied even to geological problems. The possibility of finding electrical potentials in bore holes, however, seems to have been overlooked during the early years of electric well logging, and it was only after several years that it was realized that significant potentials were generated in the bore hole itself. These potentials can be classified in the two following groups:

(1) The potentials which are found in the ground even when no bore hole exists. They can be observed in mines, shafts, and holes containing no drilling fluid, and are considered to be contact potentials occurring between different beds of sedimentary formations. They are called natural potentials.

(2) The potentials found in bore holes containing drilling fluids. These seem to be caused by one main factor, electrochemical reactions, similar to those of a concentration cell. These potentials are called secondary potentials.

A detailed discussion on the theories of these potentials and their application in electric logging can be found in Guyod's excellent series of articles on the subject, (3,4) and other publications (12).

The studies of the electric logs in this

thesis are confined to the spontaneous potential curve as this corresponds closely in profile to the gamma ray curve of the radioactivity log (Figures 2-3 and 2-5).

Instrumentation:

The well head set-up for making an electrical survey is similar to that shown in Figure 2-1 for a radioactivity survey except that no separate instrument truck is used. The instruments, recorder and hoist apparatus are all contained in the one truck. The equipment used consists of a sonde, a cable, a control panel containing the necessary circuits, a pulsator, and a photographic recorder. In addition, batteries or a direct current generator are carried to serve as a source of current in recording the resistivity.

The sonde is a system of electrodes, mounted on an insulated mandrel, which is lowered into the hole on the end of the cable, to which it is connected by means of a threaded sleeve. The cable passes over a sheave at the surface, located above the hole, and in order to raise or lower the sonde in the hole, the cable is wound or unwound on a winch, set permanently on the truck and driven by the engine of the truck. The various electrodes of the sonde are connected by means of insulated conductors in the cable, through a slip

ring collector on the winch, to the appropriate terminals of the circuits in the truck.

The pulsator is used to convert direct current to a pulsated current. This device enables the resistivity curves to be recorded at the same time as the potential curve.

The cable used in modern electric well logging operations is a six-conductor, armored cable. This cable can be used in logging the deepest holes and permits many combinations of electrode arrangements to bring out particular properties desired.

The actual measurements of potentials and resistivities are made by recording galvanometers equipped with small mirrors. A photographic film is exposed by narrow beams of light reflected from these mirrors. The deflection of each beam on the film is proportional to the potential difference being recorded by that galvanometer. The circuits in the recorder are adjusted so that suitable sensitivity scales for the potential and resistivity curves are obtained. The film is made to move in the recorder in synchronism with the movement of the sonde along the hole. Each light beam traces on the film a curve, which at a position corresponding to a given depth of the sonde, has an amplitude indicative of the

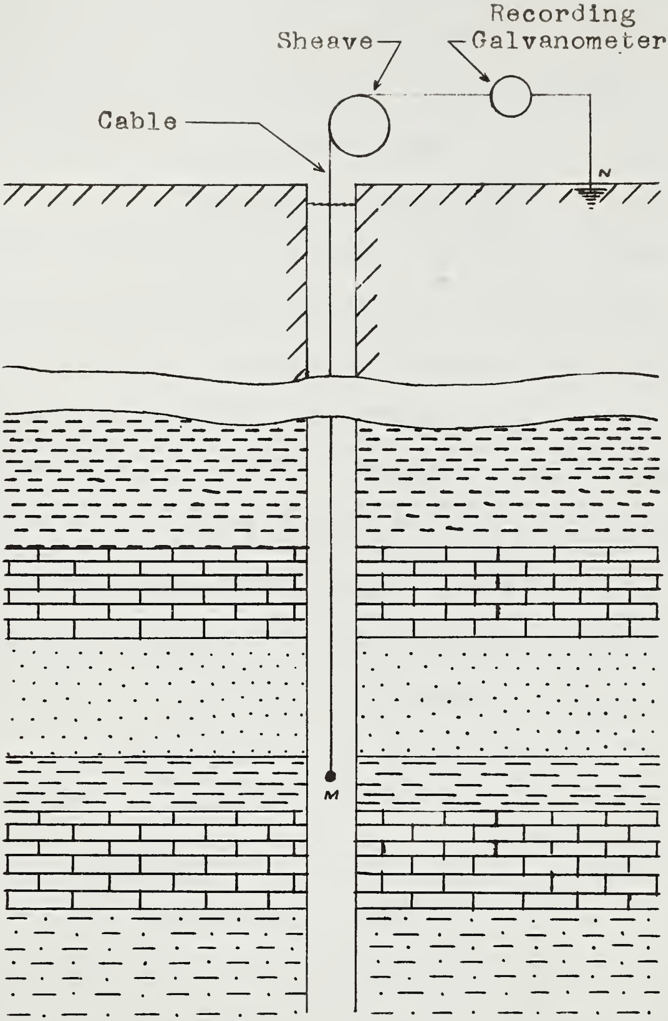


Figure 2-4. Schematic circuit for recording spontaneous potential logs. (From Schlumber Well Logging and Auxiliary Methods)

magnitude of the potential or resistivity measured at that depth.

The usual logging speed is about 6000 feet per hour in Alberta, and curves with good definition may be obtained at this speed.

The Spontaneous Potential Log:

The spontaneous potential curve is a record of the naturally-occurring potentials measured in the mud at different depths in a drill hole. It is, in effect, a record of the potential differences between a stationary electrode, N located at the surface and at a fixed potential, and a moving electrode, M, whose potential varies as it moves along the hole. The potential differences are observed by means of a recording galvanometer. Figure 2-4 is a schematic diagram of this operation.

According to the circuit shown in Figure 2-4, it can be seen that the recording galvanometer measures all the differences of potential between the electrodes. However, when the proper precautions are taken, experience has shown that, under normal conditions, the deflections on the potential log correspond to the phenomena occurring at the contacts between the mud and the different beds, and also at the contacts between the beds themselves. These phenomena produce an electric current which uses the mud as its return path. In

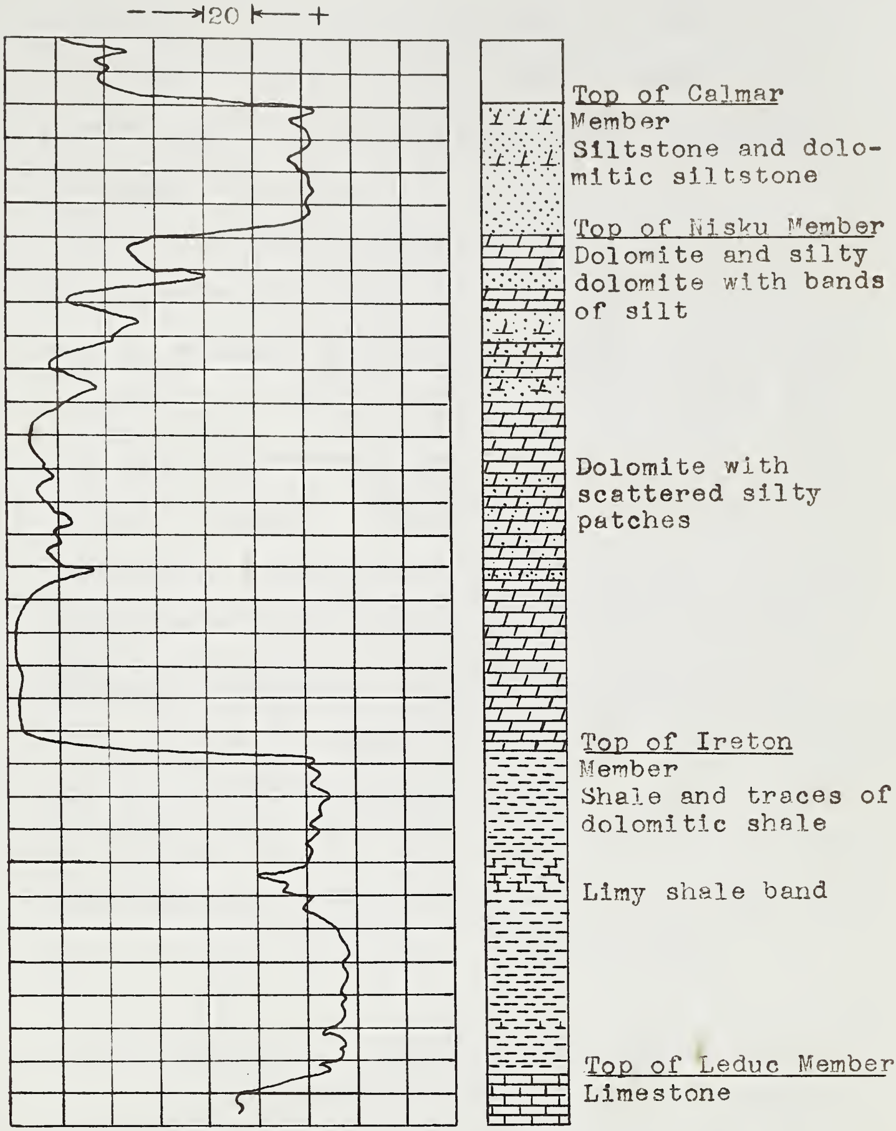


Figure 2-5. Typical Spontaneous Potential log of four Devonian formations. Geologic column at right shows log interpretation of lithology. (Imperial Opal No. 9)

doing so, it creates in the mud, by ohmic effect, potential differences which can be measured and plotted against corresponding depths to produce the potential log.

A typical potential curve of the electric log is shown in Figure 2-5. It will be noticed that no definite potential in millivolts is given on the scale. This is quite consistent with the fact that the curve is qualitative and not quantitative in aspect. The vertical lines represent a potential difference of 20 millivolts. Thus one can compute the difference in potential between adjacent formations. In practice, the curve in front of a shale formation is taken as the base line, and potential differences of other type of strata are referred to this line. In Alberta a convenient reference line is the curve representing the Colorado shale (not shown in this figure).

General Relation of Radioactivity and Electric Logs

The gamma ray curve of the radioactive log and the potential curve of the electric log are much alike in profile, as a glance at Figures 2-3 and 2-5 will show. The only explanation for this at present is the fact that the gamma log shows deflections right or left as a formation is more radioactive (shale, silt) or less radio-

active (sand, limestone).

The potential log similarly shows deflections toward the positive side, the right, for impervious beds (shale, silt) and toward the negative side, the left, for permeable beds (sand, limestone). Russell (11) has shown there is a direct relation between the permeability of the rock and its radioactivity. Using sand as an example he shows that the radioactivity increases as the permeability decreases.

Since increasing radioactivity on the gamma ray log, and decreasing permeability on the potential log cause both curves to deflect to the right, this explains, in some measure, the similarity. It must be remembered, however, that the two curves represent very different physical characteristics.

Within a formation the gamma ray log records the changes in lithology in much more detail than the potential curve, as is shown in Figures 2-3 and 2-5. This, no doubt, is because the gamma ray curve is a measurement of a fundamental property of the rock in a formation and responds to each slight change in lithology, while the potential curve measures the potential differences which are greatest at formation contacts, but are not notice-

TABLE 2-1		
UPPER DEVONIAN FORMATIONS IN THE REDWATER OIL FIELD		
Formation	Member	Character
Wabamun		Buff to creamy, vuggy dolomite where present
Winterburn	Graminia	Grey dolomite siltstone where present
	Calmar	White, green, light buff, (rarely red), calcareous to dolomitic siltstone; occasionally argillaceous. Up to 10% fine grained, pyritic sandstone may be present. The Wabamun formation and Graminia member may be eroded off, and often part of the Calmar is missing. Where erosion has not affected the member it has a remarkably constant thickness, about 40'.
	Nisku	Brown, through light buff to grey. Very fine to finely crystalline at top and bottom; middle part is medium crystalline. Silty bands occur at top and base of member, and isolated pockets of silt and silty stylolitic shale partings are present throughout. The member thins from about 150' at the north to 100' at the south end of the Redwater Field.
Woodbend	Ireton	Grey-green, silty, dolomitic shale with traces of calcite veins. Some sections approach an argillaceous dolomite. Lower half of member consists of grey argillaceous limestone to limy shale having shell fragments and crinoid debris. Over the reef the member is about 100', thickening to about 150' on the east flank.
	Leduc	Brown, with small patches of light grey and cream, limestone. Brachiopod and stromatoporoid fragments are common. The limestone is finely crystalline throughout.
	Duvernay	Brown argillaceous dolomite.

able within a relatively homogeneous formation. A comparison of the Ireton profile of the two log types will show this difference clearly.

Lithologic Description of Formations Used

This study of the radioactivity and electric logs for the Redwater Field is confined to four Paleozoic horizons, the Calmar and Nisku members of the Winterburn formation, and the Ireton and Leduc members of the Woodbend formation. A lithologic description of these members is contained in Table 2-1.

Errors in Logging the Tops of Formations

From the foregoing lithologic description of the horizons used in this study, it is apparent that they differ appreciably in composition. These differences appear in their responses, both in electrical and radioactivity logging, as can be seen in Figures 2-3 and 2-5, causing the characteristic profile of each member to appear on the log well separated from adjacent members.

The ideal log of the formations, whether radioactive or potential, would have a straight horizontal line joining the profiles of adjacent formations at their contacts, and this straight horizontal line would merely represent the de-

flection of the recorder pen in registering the differences in potentials or radiation intensities of the two formations. This line would be a true "transition" line.

The ideal is impossible in both types of logging for several reasons. In both cases the recording pen lags behind the impulses of the bore hole instrument. Hence, in moving from one deflection on the log to another, the movement of the paper will bend the transition line off horizontal. This factor is important in electric logging where the potential measuring electrodes may be considered as a point, as it is really the only factor preventing a horizontal transition line at formation contacts.

A second factor which occurs in making a radioactivity log, and tends to put the transition line off from horizontal, is the length of the ionization chamber. Since this chamber is three feet long it introduces a vertical error. As the chamber passes from one formation to the next it is affected by the radiations of the succeeding formation in ever increasing measure, and conversely, the formation left behind affects it less and less. It is easily seen that the full radiation of the formation entered will not affect the ion-

ization chamber until it has passed through a distance of three feet. The transition line thus acquires a further slant. The time constant control, in averaging out the changing radiation intensities at formation contacts, smoothes the transition line. However, if it is not set exactly to the logging speed it will either cause a further lag, if set to average over too short a period, or will make the transition line jagged and almost illegible. The time constant control in use today is preset to a logging speed of approximately 60 feet per minute, and as the logging of the section under study is done at from 22 to 28 feet per minute, a further lag is introduced into the pen recorder. The sum total of these pen lags is not great, rarely causing the vertical separation to be more than four feet. However, an occasional log shows a separation of up to 10 feet.

Methods of Study

Determination of Formation Tops From Logs:

The determination of formation tops from a radioactivity log depends, to some extent, on individual interpretation. Several methods are advocated, one being that the correct position of the contact plane is found at a point one third the distance from the maximum peak to the

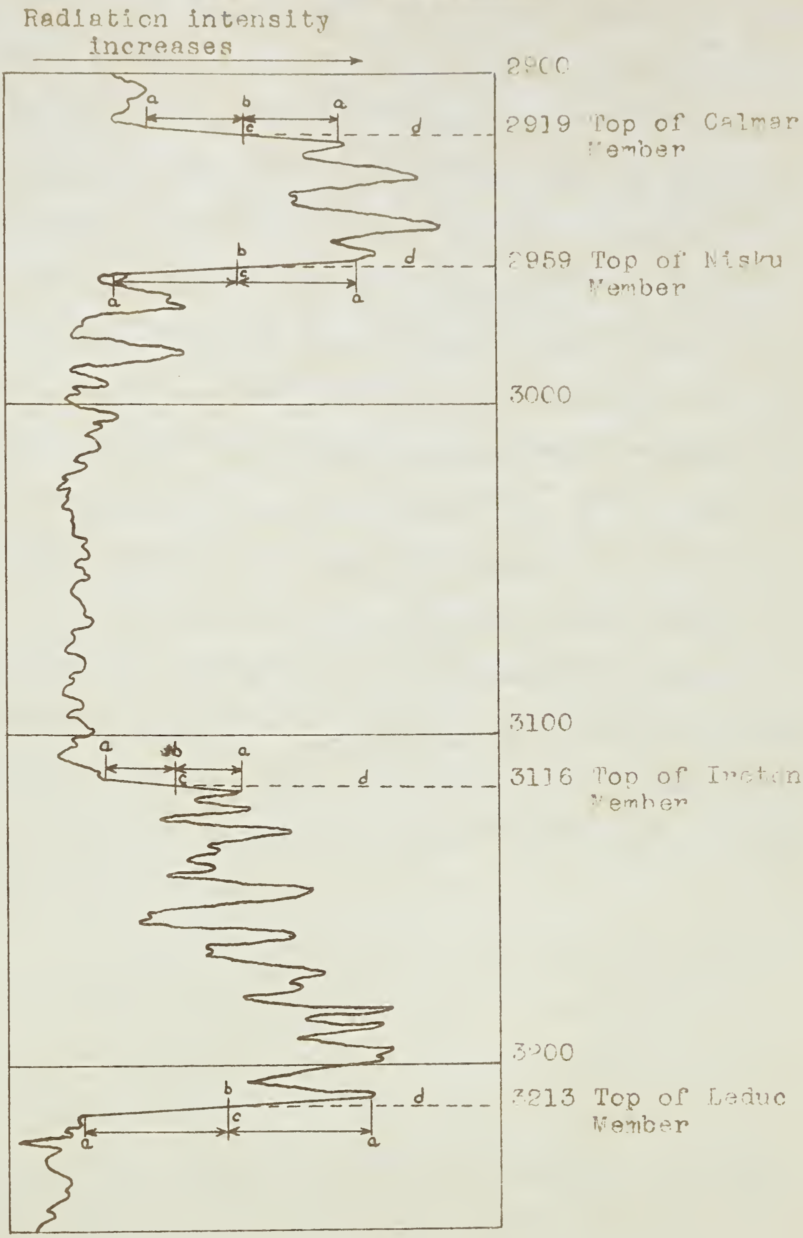


Figure 2-6. Method of determining formation contacts from gamma-ray log. (See text for explanation.)

minimum peak of adjacent profiles. Another method is to determine the point midway on the transition line (6, 13). From the foregoing discussion on the ionization chamber's passage from one formation to the next, it would appear that when the midpoint of the chamber is opposite the contact, the corresponding point on the transition line should be taken as the correct depth of the contact. It is also apparent that if the time constant control is set correctly, or nearly correctly, this point should be half-way along the transition line.

On an electric log the contact plane between two formations is represented by an inflection point in the potential curve,(4). It was observed by the writer that this point occurs half way along the transition line of this curve in the majority of logs.

To obtain uniformity in the work, the same method of determining tops of formations is used on both types of logs. This method is illustrated in Figures 2-6 and 2-7. The transition line of the gamma ray curve is usually a straight line, and is picked out quite easily from the profile curve. Vertical lines (a) are drawn from each end of the transition line and the horizontal distance between them is measured. From the midpoint (b) between the end points of the transition

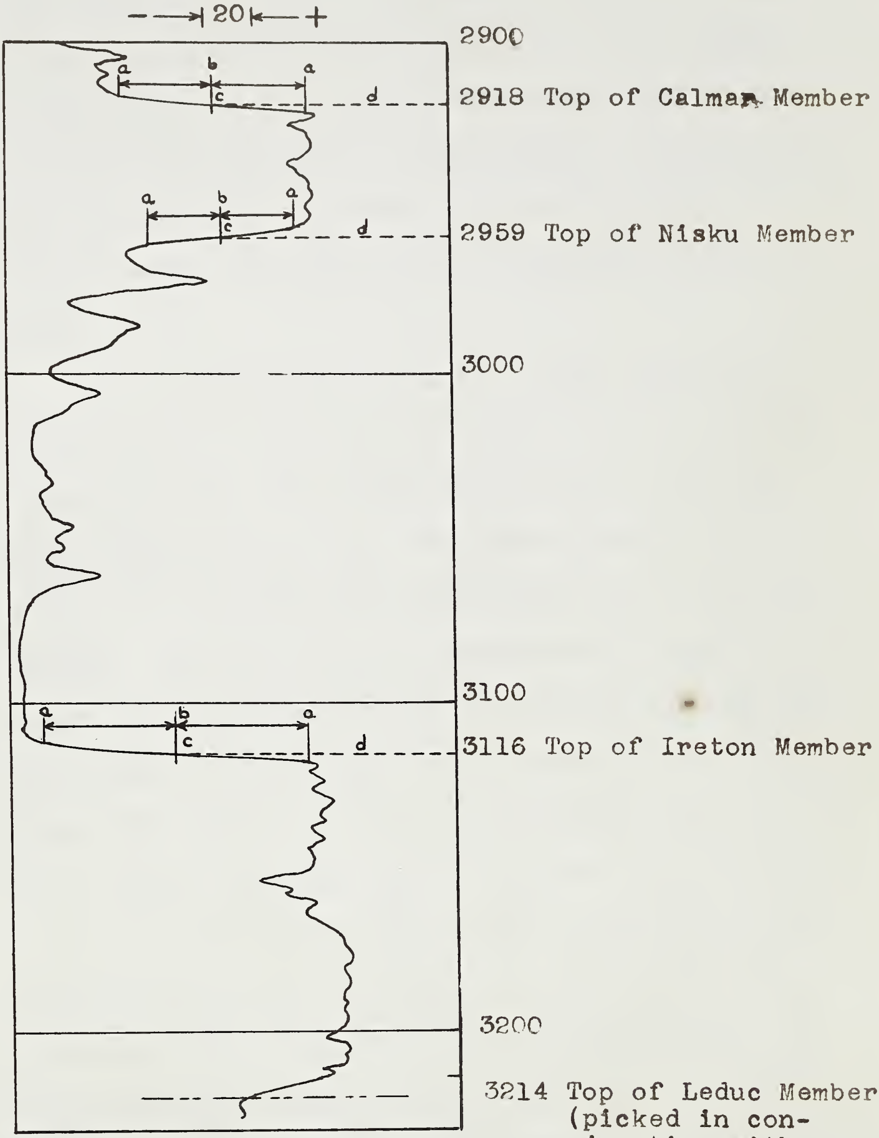


Figure 2-7. Method of determining formation contacts from spontaneous potential log (See text for explanation)

line a vertical line (c) is drawn to intersect the transition line. The point of intersection is then projected horizontally (d) to the scale on the side of the log and the depth read to the nearest foot, except in cases where it is exactly on the half foot. As the scale of the log is 2 inches equal 100 feet, a 50:1 engineer's rule is used.

The transition line of the potential curve is not so distinct as that of the gamma ray curve, and for this reason the points where the line flattened out from the characteristic profiles of formations are considered to be the end points. The procedure of determining the mid-point of the transition line, and the reading of the depth of this point is the same as for the gamma ray curve. In some of the wells used in this study, the hole was not drilled deep enough into the Leduc Member before the electric log was taken to allow the potential curve its full deflection. The transition line is therefore only partially represented on the log. The top of the Leduc Member is taken from the resistivity curve in these cases, as is shown in Figure 2-7.

Frequent checks are necessary to ensure that the point of intersection of the vertical line (c) and the transition line coincide with

the midpoint of the gamma ray transition line, and the inflection point of the potential curve.

Results

Radioactivity and electric logs of 85 wells in the Redwater Field are used in this study. The tops of the four previously mentioned formations are determined and presented in Tables 2-2 and 2-3 of Appendix 2-A. The locations of the wells used, together with their identifying reference numbers, are plotted on the map of the Redwater Field found in the pocket on the inside back cover. An index of wells is found in Appendix 2-B.

Discussion of Results

In the following discussion reference is made only to Table 2-2. However, the remarks apply also to Table 2-3.

Columns 2 and 3 in Table 2-2 show the total depth of the well as recorded by the driller and radioactivity log respectively. Before a survey is taken the drill pipe is "measured out of the hole" by the drilling crew. This consists of measuring each length of pipe as it is removed from the hole and is stacked in the derrick. The measurement is usually quite accurate as it must agree with the pipe tally, kept while drilling is in progress. There may be a certain amount of

error in this measurement as the pipe hanging in the hole is bound to stretch somewhat and the stretch cannot be taken into account in the measurement. It is the writer's opinion, however, that this error is not appreciable. In this thesis the driller's depth is taken as the true depth of the hole.

Good drilling practice demands that the mud in the drill hole be circulated for at least one hour before a survey is run. This is to clear the hole and remove any cavings from its bottom, and the mud. It is assumed here that the practice has been followed in the wells used. Any discrepancy between the driller's depth and the radioactivity log depth, therefore, is an error on the part of the logging apparatus, or the operator of the apparatus.

The difference between the driller's depth and radioactivity log depth is shown in column 4 under Correction Factor (CF). The plus figures indicate the driller's depth is greater than the log depth, and the minus figures indicate that the log depth is greater. It is reasoned that, if the radioactivity log depth is greater than the driller's (or true) depth, then the error will also be found in the depths at which the log shows the formation contacts. Thus, if a radioactivity log

shows a hole to be 4003 feet deep while it is really 4000 feet, and a formation contact is shown to be at 3003 feet on the log, it is assumed that the log is 3 feet too deep here also. Thus the true depth of the formation is 3000 feet. The correction factor in this case would be -3 feet.

The correction factor found in each well is applied to the depths of the contacts determined from the log and is recorded in its appropriate column.

The accepted depths of the formation contacts, as given in the Schedule of Wells Drilled for Oil and Gas to 1949, and Weekly Reports of the Alberta Petroleum and Natural Gas Conservation Board, are shown in columns 7,10,13 and 16 of Tables 2-2 and 2-3. These are used as the standard with which to compare the accuracy of the radioactivity and electric logs. It would be preferable to have cored depths of contacts in wells where this is possible, or accurate sample depths, for comparison; however this information is not obtainable. The Board determinations are made by using electric logs. When a contact depth is determined this depth is checked in the samples of the bit cuttings for that well and any necessary correction made to the original depth determination. It is rather unfortunate that the electric logs

TABLE 2-5

	Ru : Eu	Rc : Ec	Rc : CBD	Ec : CBD
LEDUC MEMBER				
Standard Deviation (SD_1)	2.9	4.1	3.4	2.7
No. of Readings	67	67	74	67
Standard Deviation (SD_2)	3.7	5.4	4.8	3.5
No. of Readings	72	72	78	70
IRETON MEMBER				
Standard Deviation (SD_1)	3.1	4.0	3.6	2.5
No. of Readings	77	77	75	74
Standard Deviation (SD_2)	3.6	5.0	4.2	3.8
No. of Readings	82	82	78	77
NISKU MEMBER				
Standard Deviation (SD_1)	3.8	4.4	4.7	3.8
No. of Readings	65	65	63	69
Standard Deviation (SD_2)	4.5	6.3	7.3	4.3
No. of Readings	77	77	70	76
CALMAR MEMBER				
Standard Deviation (SD_1)	3.5	4.4	5.5	5.2
No. of Readings	59	59	47	54
Standard Deviation (SD_2)	8.3	(Too large to be significant)		
No. of Readings	74			
SUMMARY FOR FOUR MEMBERS				
Standard Deviation (SD_1)	3.3	4.2	4.2	3.6
No. of Readings	268	268	259	264

Standard deviations of log readings taken in Table 2-4, Appendix 2-A.

Key to subhead symbols:

Ru:Eu - Radioactivity contact depth versus Electric log depth, uncorrected.

Rc:Ec - Radioactivity contact depth versus Electric log depth, corrected by application of respective correction factors.

Rc:CBD- Corrected radioactivity contact depth versus Conservation Board depth.

Ec:CBD- Corrected Electric log contact depth versus Conservation Board depth.

are used in the determination as this introduces the possibility that the comparisons are merely between the writer's and another person's interpretation of the logs. Of course the sample check gives some control over the accuracy.

Table 2-4 is a detailed tabulation of the differences between the two types of logs, and between each log type and the Conservation Board figures. Two sets of standard deviations of the various readings are shown at the base of each column, together with the number of wells used for the particular determination. These are summarized in Table 2-5.

These two sets of standard deviations are necessary because of the large deviation of certain of the readings. One example might be Well IO 14. In this well the uncorrected radioactivity depth of the Leduc Member varies from the electric log depth of the same Member by 19 feet. The corrected depths vary by 16 feet. An inspection of the rest of the wells shows that, with a few exceptions, the variation is on the order of from 1 to 5 feet. Thus, if the variation of IO 14 and other wells like it were included in the total deviation calculations, the standard deviations would be abnormally large, and would not reflect the true state of affairs. The writer

set an arbitrary limit of plus or minus 15 feet as the maximum deviation allowed, and the first set of standard deviations (SD_1) are calculated with this in mind. The readings deleted in calculating this set are marked with an asterisk. The second set of standard deviations (SD_2) are calculated using all the deviations irregardless of amplitude, and show the effect of the few wells deleted in the first set of calculations.

Relation of Radioactivity and Electric Log Determinations:

One would expect, from the discussion of the correction factor above, that the standard deviation of the corrected radioactivity and electric logs would be less than that of the uncorrected log. Table 2-5 shows that the opposite is true in all cases. This shows that there must be an error in the assumption discussed. This error could arise from several sources: (a) There could be cavings in the hole holding the logging instrument off bottom. If this is the case then the correction factor of a plus figure has no relation to the contacts of the formation as logged; (b) The instrument might get stuck in the hole above bottom. Usually this occurs far enough off bottom to be obvious; (c) The driller's depth might be wrong. Of these three possibilities the first is the most likely to be the cause of an

TABLE 2-6

	Ru : Eu	Rc : Ec	Rc : CBD	Ec : CBD
LEDUC MEMBER				
Standard Deviation	2.9	3.5	2.6	2.5
No. of Readings	30	30	42	49
IRETON MEMBER				
Standard Deviation	2.9	2.6	2.9	3.3
No. of Readings	29	29	43	48
NISKU MEMBER				
Standard Deviation	4.3	4.7	4.9	3.3
No. of Readings	30	30	36	45
CALMAR MEMBER				
Standard Deviation	3.8	4.7	4.9	5.2
No. of Readings	24	24	28	38
SUMMARY OF FOUR MEMBERS				
Standard Deviation	3.5	3.9	3.8	3.6
No. of Readings	113	113	149	180

Standard deviation of log readings using only wells with zero or minus correction factors.

Key to subhead symbols as in Table 2-5.

error. If then , we say that all cases where the logging apparatus has registered the bottom of the hole at shallower depths than the driller, are due to cavings in the hole bottom, the only errors in the logs are when they register total depths greater than the driller's.

It is not the writer's opinion that in all cases, where the logging apparatus shows a hole depth less than the driller's, that the hole bottom has a layer of cavings, and that there is no log error. There is, however, no way of telling which holes are caved and which ones are not. If then, we omit all the holes in which the logged depth is less than the true depth, and consider only those holes in which the logged depth is greater than the driller's depth, we obtain the results shown in Table 2-6.

Only those wells in which the correction factor is minus, or zero, in both radioactivity and electric logs, are used in the comparison of the logs with each other. All logs showing minus correction factors are used for comparison with the accepted depth.

If Table 2-6 is compared to Table 2-5, it is seen that the deviations of the corrected logs in the Leduc and Ireton Members is reduced, while those of the Nisku and Calmar Members are

increased slightly. It should also be noted that the deviations of the uncorrected logs for the first two mentioned members is unchanged, while those of the second two are increased materially. The overall result of this is to reduce the deviation of the corrected logs. This is shown in the standard deviation of the total readings where, in the case of the corrected logs, the deviation is reduced, and for the uncorrected logs increased slightly.

No doubt some of the wells having positive correction factors also were logged to total depth without interference from cavings. However, as mentioned before, it is impossible to pick these wells out. The writer is convinced that, if they were included, the deviations of the corrected logs would be even less. Until such time as the logging instruments have some means of indicating whether they are at the well bottom, stuck up the hole, or in cavings, a correction may be reliably applied only to those cases with a minus correction factor.

The logs having minus or zero correction factors show another feature. This is the constancy of the plus or minus deviation between the corrected logs for a formation. Of the thirty readings of the Leduc formation, twenty-four or 80 percent of the readings show the radioactivity log recording

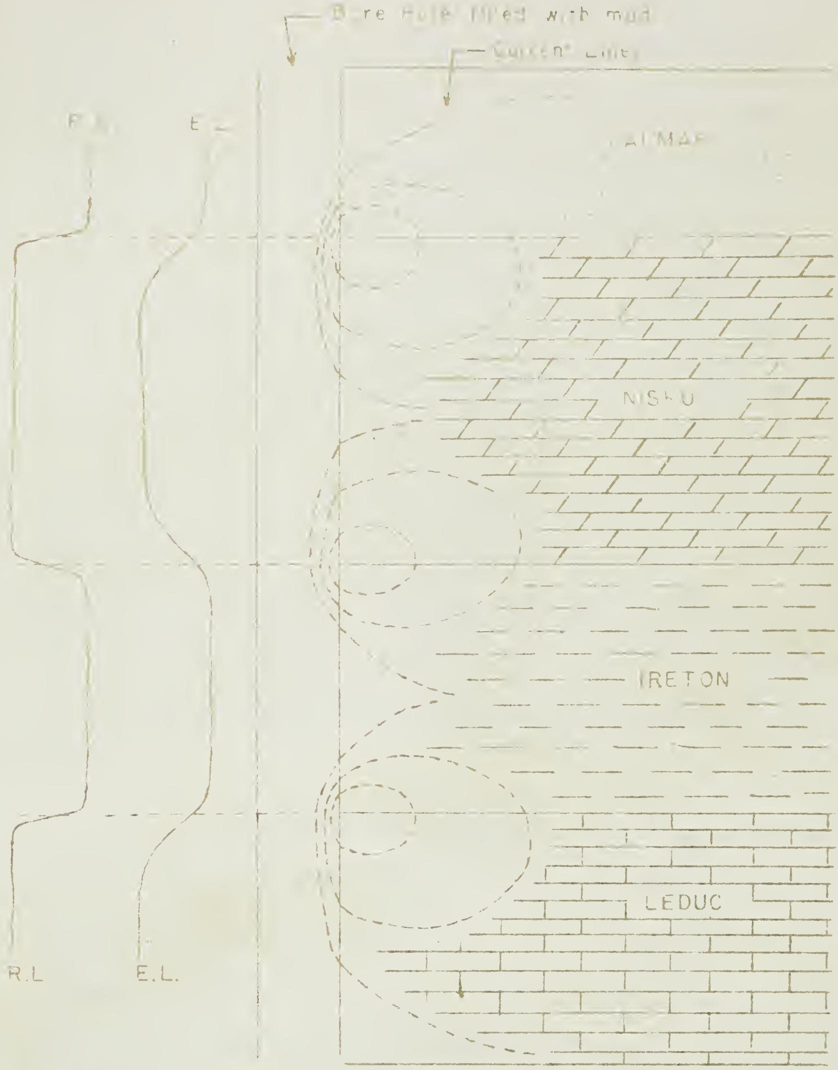


Figure 2-8. Current line patterns near shale-mud-limestone boundaries in the Redwater oil field. The effect of the current lines is shown on the potential log (E.L.) which is compared to the gamma-ray log (R.L.) of the section. After Guyod (7).

higher than the electric log. The Ireton readings produce the opposite results - the radioactivity log recording deeper than the electric log in 25 out of 29 readings, or in 86% of the readings. The radioactivity log again records the Nisku top shallower than the electric log in 90% of the readings. The Calmar readings are divided, the radioactivity log showing 13 tops deeper, and 11 tops shallower than the electric log. The Calmar readings are therefore unreliable as they show no pattern. This feature might be used in testing the log to see if a correction factor is needed, or can be applied. If the corrected depth follows the pattern mentioned above for the three lower formations, then the correction is probably all right.

A possible explanation for the observed pattern in the three deeper formations can be obtained by a consideration of the electrical potential developed around a shale-limestone contact. The Leduc-Ireton contact may be taken as an example. (Figure 2-8).

It has been shown experimentally (3,12) that the current at such a contact flows from the shale through the mud and back into the limestone or dolomite as the case may be. If the resistances of the two rock types were approximately

the same, the current paths would form a series of ellipses. The resistance of limestone, however, is many times that of shale and this resistance actually repulses the current lines. Instead of flowing in the regular elliptical patterns, the current is repulsed by the Leduc limestone in the bore hole below the boundary. This effect straightens the current lines situated in the bore hole below the contact and lengthens the path the current follows in the mud column. Therefore, there is still an appreciable amount of current flowing in the bore hole several feet below the boundary, which means the potential drop will be observed for a relatively long section in this zone. The effect also decreases the potential gradient opposite the limestone bed so that the log has a more rounded shape below the contact. This effect occurs at the contacts of each of the three lower members studied in this thesis with the results shown in Figure 2-8.

The inflection point of the potential log is still opposite the shale-limestone contact, but the rounding of the curve in the limestone section obscures this point. The result is a straightened portion of the potential log transition line covering a vertical distance of several feet. The contact of the formations may be

picked anywhere along this portion of the curve. The writer, using the method of contact determination described previously, found that in every case the mid-point of the log line fell within this straightened portion of the potential curve.

From the foregoing discussion one can realize that the determination of a shale-limestone contact may vary by several feet unless a very great deal of care is used to find the inflection point, if it is possible to find this point at all. The radioactivity log, on the other hand, is affected only by the difference in the radiation intensity of the formations, and the mid-point of the transition line is usually a very accurate determination of the formation contact. It is the writer's opinion, therefore, that the gamma ray log gives more accurate contact determinations than the electric logs for the formations used in this thesis.

Relation of Radioactivity and Electric Logs to Accepted Depths:

The Conservation Board's method of determining the tops of formations has been discussed previously. As might be expected, the standard deviation of the electric log depths is less than that of the radioactivity log depths. A rather surprising feature is the close agree-

ment of most of the determinations of the writer with those of the Board. In a few cases such as IS 22, and IS 24, where the writer's contact determination by the potential curves and gamma ray curves agree closely with each other, but differ appreciably from the Board determinations, it is apparent that the Board figures are wrong. These readings have therefore been left out of the deviation calculations (SD_1).

The deviation of the Calmar contact, as picked from gamma ray and potential curves by the writer, from the Board figures, appear to be somewhat higher than normal (Table 2-5). This is due no doubt, to the Board's having samples to correct their readings with in wells where the top of the Calmar is eroded, while the writer's figures are from log determinations only.

Relation of Radioactivity Log Determinations to Board Depths:

As can be seen from Table 2-5, in general, the determinations from the gamma ray curve agree closely with the accepted depth. The maximum error shown in the table, excluding the Calmar Member is 9.4 feet, and if the Calmar is included, 11.1 feet, while the average error is less than 8.4 feet. An examination of Table 2-4 will show that 80% of the determinations fall

within the average standard deviation of 4.2 feet from the accepted depth.

Table 2-6 shows even closer agreement between the determinations from the radioactivity logs and the Board figures, the average deviation here being 3.8 feet. This is further evidence that the minus correction factor indicates that an error exists in the log and that a correction can safely be applied.

Relation of Electric Log Determinations and Board Depths:

The electric log determinations show very close agreement with Board figures throughout. The maximum error shown is 10.4 feet in the Calmar Member, and the possible reason for this has already been discussed.

The deviations shown in both tables can be accounted for by the different interpretation of the contact point on the log by different people. The Board determinations are done by reading the combination of resistivity and potential curve profiles, while the writer used the potential curve only. The deviation of the Calmar is again above normal probably for the reason mentioned before.

Conclusions

The general conclusions reached as a

result of this study are as follows:

1. Radioactivity and electric logs are both useful in determining the depths of formation contacts. The formation tops recorded by the gamma ray log are probably more accurate than those determined by the spontaneous potential log.
2. There are errors in both types of logs, which, although not great, are discernible.
3. Correction of log errors is not possible in all cases. It is possible in those cases in which the logged depth of the hole is greater than the true depth.
4. A pattern of plus and minus deviations between the contacts as logged by the radioactivity and electric log is observed. This suggests that a correction factor could be derived and successfully applied in correcting both types of logs.

The conclusions which can be reached after a study of this nature are somewhat nebulous, due to the lack of a definite standard. The accepted depths (Conservation Board depths) used here as that standard, have been shown, in some cases, to be in error. Further study, comparing the logged contacts to definite cored contact depths, is indicated.

BIBLIOGRAPHY

1. Bush, R.E. and Mardock, E.S.;(1950): Some Preliminary Investigations of Quantitative Interpretations of Radioactivity Logs; Jour. Petroleum Technology, Vol. 189.

2. Fearon, R.E.; (1945): Radioactivity Well Logging; The Oil Weekly, June 4 and 11.

3. Guyod, Hubert; (1944): Electrical Well Logging; The Oil Weekly, Aug. 7 to Dec. 24.

4. -------------; (1945): Electric Log Interpretation; The Oil Weekly, Dec. 3 to 24.

5. Jackson, W.J. and Campbell, J.L.P.; (1946): Some Practical Aspects of Radioactivity Well Logging; Trans. Amer. Inst. Min. Met. Eng., Vol. 165.

6. Lane-Wells Company; (1947): Radioactivity Well Logging; Tomorrow's Tools, Today!, Bull. RA-47-B-1.

7. Leroy, L.W. and Crain, H.M.; (1949): Subsurface Geologic Methods; Colo. School of Mines;first edition.

8. Long, W.D.; (1950): Theory of Radioactivity Logging and its Usage in Western Canada; Can. Oil and Gas Industries, Vol. 3, No. 5.

9. Mercier, V.J.; (1950): Radioactive and Electrical Logging; World Oil.

10. Russell, W.L.; (1941): Well Logging by Radioactivity; Bull. Amer. Assoc. Pet. Geol., Vol. 25, No. 9.

11. -------------; (1944): The Total Gamma Ray Activity of Sedimentary Rocks as Indicated by Geiger Counter Determinations; Geophysics, Vol. 9, No. 2.

12. Schlumberger Well Surveying Corp.; (1949): Review of Schlumberger Well Logging and Auxiliary Methods; Schlumberger Document No. 2.

13. Shepherd, G.F.; (1944): Use of Gamma Ray Logs in Measurement Problems; The Oil Weekly, May 8.

APPENDIX 2-A

TABLE 2-2: Contact Determinations from Radioactivity (Gamma Ray) Curve

TABLE 2-3: Contact Determinations from Electric (Potential) Log Curve

TABLE 2-4: Comparison of Readings Taken from Tables 2-2 and 2-3

<u>Explanation of Tables</u>

Tables 2-2 and 2-3:

1. Blank spaces in contact determinations indicate that either the section of the well is not represented on the log or the transition line of the contact is such that no reliable determination can be made.

2. Blank spaces in the Conservation Board depths indicate that the well is not listed in the reports cited.

Key to Subhead Symbols:

Column 1 WRN - Well Reference Number

2 RDL - Total Depth of well recorded on log

3 TD - Total Depth recorded by driller

4 CF - Correction Factor

5,8,11,14 - RD - Depth of Contact recorded by log

6,9,12,15 - CD - Corrected Depth of contact

7,10,13,16- CBD- Depth of Contact recorded by Conservation Board

Table 2-4:

1. Blank spaces indicate no comparisons are possible because one component is missing.

2. In columns where radioactivity logs are compared with electric logs, or Conservation Board depths, plus figures indicate the radioactivity log contacts are shallower than the other depths.

3. Where electric log contact depths are compared to Conservation Board depths, plus figures indicate the logged depth is less than Board depth.

4. Figures marked with an asterisk are beyond the arbitrary 15 foot limit set for determining the standard deviations.

Key to Subhead Symbols:

Column	Symbol	Meaning
1	WRN	Well Reference Number
2,6,10,14	Ru:Eu	Radioactivity contact depth versus Electric log depth uncorrected (RD of Tables 2-2 and 2-3)
3,7,11,15	Rc:Ec	Radioactivity contact depth versus Electric log depth, corrected by application of respective correction factors. (CD of Tables 2-2 and 2-3)
4,8,12,16	Rc:CBD	Corrected radioactivity contact depth versus Conservation Board depth

5,9,13,17 - Ec:CBD - Corrected Electric log contact depth versus Conservation Board depth.

The standard deviation SD_1 is found using only the deviations of less than 15 feet in the Table. SD_2 is the standard deviation of all the readings. The number of readings used in each case is shown in the line N.R.

TABLE 2-2

Contact Determinations from Radioactivity (Gamma-Ray) Curve

W R N	General			Leduc Member			Ireton Member			Nisku Member			Calmar Member		
	R D L	T D	C F	R D	C D	C B D	R D	C D	C B D	R D	C D	C B D	R D	C D	C B D
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
I R 1	3329	3326	-3	3178	3175	3175	3087	3084	3085	2960	2957	2960	2908	2905	2920
2	3304	3310	+6	3163	3169	3165	3078	3084	3080	2958	2964	2962	2902	2908	2910
3	3255.5	3256	+0.5	3138	3138.5	3145	3003	3003.5	3000						
4	3272	3276	+4	3156	3140	3157	3064	3068	3065	2940	2944	2943	2897	2901	2900
5	3208.5	3208	-0.5	3044	3043.5	3044	2943	2942.5	2940	2816	2815.5	2820	2774	2773.5	2775
7	3119	3119	0	3088	3088	3090	2976	2976	2980	2834	2834	2802	2770	2770	2755
8	3246	3247	+1	3135	3136	3135	3008	3009	3010	2864	2865	2865	2818	2819	2820
9	3282	3282	0	3186	3186	3187	3053	3053	3055						
10	3305	3304	-1	3161	3160	3160	3025	3024	3025						
11	3325	3325	0	3179	3179	3181	3045	3045	3048	2905	2905	2907	2855	2855	2868
12	3288.5	3288	-0.5	3200	3199.5	3201	3065	3064.5	3065	2923	2922.5	2923	2866	2865.5	2885
13	3285.5	3281	-4.5	3175	3170.5	3174	3041	3036.5	3037	2905	2900.5	2904	2859	2854.5	2855
I O 14	3303	3305	+2	3218	3220	3234	3123	3125	3125	2979	2981	2977	2941	2943	2940
16	3294	3295	+1	3213	3214	3213	3116	3117	3116	2959	2960	2959	2919	2920	2920
17	3262.5	3257	-5.5	3173	3167.5	3173	3079	3073.5	3080	2942	2936.5	2944	2903	2897.5	2902
18	3324	3328	+4	3159	3163	3165	3067	3071	3067	2930	2934	2931	2853	2857	2895
19	3346	3345	-1	3270	3269		3157	3156							
20	3221	3219	-2	3176	3174	3177	3085	3083	3083	2937	2935	2937	2895	2893	2897
I S 21	3266.5	3265	-1.5	3138	3136.5	3133	3035	3033.5	3036	2934	2932.5	2938	2895	2893.5	2900
22	3295	3296	+1	3094	3095	3138	2977	2978	3034	2861	2862	2927	2847	2848	2888
23	3264.5	3265	+0.5	3122	3122.5	3121	3013	3013.5	3010	2907	2907.5	2906	2873	2873.5	2875
24	3269	3267	-2	3080	3078	3102	2959	2957	2980	2893	2891	2865	2875	2873	
I A 25	3266	3265	-1	3147	3146	3146	3054	3053	3050	2948	2947	2952	2905	2904	2900
26	3227.5	3229	+1.5	3194	3195.5	3194	3029	3030.5	3030	2949	2950.5	2905	2909	2910.5	2860
27	3255.5	3256	+0.5	3119	3119.5	3116	3013	3013.5	3005	2892	2892.5	2890	2848	2848.5	2845
28	3221	3223	+2	3093	3095	3093	2986	2988	2980	2889	2891		2856	2858	
29	3263.5	3264	+0.5	3157	3157.5	3061	3045	3045.5	3050	2950	2950.5	2964	2894	2894.5	2915
30	3263.5	3264	+0.5	3163	3163.5	3162	3068	3068.5	3068	2962	2962.5		2914	2914.5	2920
31	3215.5	3216	+0.5	3098	3098.5	3098	2974	2974.5	2975						
32	3252	3253	+1	3070	3071	3068	2959	2960	2960	2859	2860	2860			
33	3278	3279	+1	3202	3203	3202	3054	3055	3053	2915	2916	2915	2863	2864	2874
34	3278.5	3281	+2.5	3225	3227.5	3230	3065	3067.5	3070	2939	2941.5	2945	2885	2887.5	2905
35	3270.5	3272	+1.5	3199	3200.5	3202	3107	3108.5	3106	3010	3011.5	3015	2956	2957.5	2977
36	3218	3218	0	3086	3086	3086	2970	2970	2970	2862	2862	2870	2828	2828	2830
37	3255	3255	0	3081	3081	3082	2976	2976	2975	2874	2874	2878	2836	2836	2840
38	3216	3215	-1	3105	3104	3106	2972	2971	2970	2860	2859	2870	2824	2823	2820
39	3247	3247	0	3167	3167	3167	3029	3029	3028	2905	2905	2905	2866	2866	2864
40	3255	3257	+2	3135	3137	3135	3004	3006	3005	2894	2896	2900	2855	2857	
I E 41	3237.5	3235	-2.5				3062	3059.5	3063	2921	2918.5	2920	2878	2875.5	2880
42	3283.5	3285	+1.5	3099	3100.5	3100	2993	2994.5	2995	2854	2855.5	2857	2804	2805.5	2820
44	3230.5	3230	-0.5	3091	3090.5	3093	3009	3008.5	3010	2873	2872.5	2870	2830	2829.5	2825
45	3317	3318	+1	3169	3170		3060	3061		2924	2925		2882	2883	
46	3219	3217	-2	3106	3104	3108	3029	3027	3030	2887	2885	2890	2849	2847	2850
47	3175.5	3176	+0.5	3128	3128.5	3133	3043	3043.5	3045	2908	2908.5	2910	2866	2866.5	2870
48	3252	3250	-2	3201	3199	3205	3112	3110	3108	2966	2964	2967	2917	2915	2920
49	3178	3174	-4	3133	3129	3132	3030	3026	3030	2873	2869	2895	2841	2837	2850
50	3302	3303	+1	3210	3211	3214									

TABLE 2-[illegible] (Cont'd.)

Contact Determinations from Radioactivity (Gamma-Ray) Curve

W R N	General			Leduc Member			Ireton Member			Nisku Member			Calmar Member		
	R D L	T D	C F	R D	C D	C I D	R D	C D	C B D	R D	C D	C B D	R D	C D	C B D
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
I E 51	3303	3303	0	3169	3169	3169	3070	3070	3072	2928	2928	2930	2890	2890	2889
53	3254.5	3255	+0.5	3135	3135.5	3136	3028	3028.5	3030	2891	2891.5	2930	2847	2847.5	2846
54	3312.5	3303	-9.5	3176	3166.5	3173	3086	3076.5	3083	2946	2936.5	2946	2902	2892.5	2900
55	3300.5	3298	-2.5	3177	3174.5	3175	3077	3074.5	3073	2937	2934.5	2931	2890	2887.5	2886
56	3336.5	3339	+2.5	3163	3165.5	3163	3064	3066.5	3063	2916	2918.5	2920	2875	2877.5	2876
57	3298.5	3296	-2.5	3192	3189.5	3192	3064	3061.5	3065	2915	2912.5	2915	2868	2870.5	2870
58	3293	3295	+2	3148	3150	3150	3041	3043	3040	2894	2896	2895	2850	2852	2860
R R 1	3206	3204	-2	3122.5	3120.5	3120	3012	3010	3010	2895	2893	2885	2839	2837	
2	3253.5	3252	-1.5	3180	3178.5	3178	3049	3047.5	3045	2899	2897.5	2905	2865	2863.5	2855
3	3274	3270	-4	3217	3213	3213	3077	3073	3075	2932	2928	2928	2872	2868	2900
4	3272.5	3272	-0.5	3214	3213.5	3211	3071	3070.5	3065	2925	2924.5	2925	2875.5	2875	2880
R T 5	3142.5	3143	+0.5	3087.5	3088	3089	2939	2939.5	2940	2809	2809.5	2818	2770	2770.5	2770
6	3177	3177	0	3113	3113	3114	2973	2973	2975	2847	2847	2848	2810.5	2810.5	2810
7	3232	3209	-23	3095	3072	3093	2973	2950	2970	2863	2840	2862	2828	2805	2830
8	3220	3228	+8	3107.5	3115.5	3106	2991	2999	2990	2868	2876	2867	2834	2842	2845
9	3163	3159.5	-3.5	3028	3024.5	3030	2912	2908.5	2915	2801	2797.5	2805	2763	2759.5	2785
10	3159	3160	+1	3033	3034	3033	2915	2916	2910	2798	2799	2800	2773	2774	2775
11	3149.5	3153	+3.5	3086	3019.5	3086	2946	2949.5	2945	2816	2819.5	2818	2781	2784.5	2780
12	3149.5	3149.5	0	3071	3071		2930	2930		2795	2795		2762	2762	
13	3205.5	3216	+10.5	3100	3110.5	3100	2966	2976.5	2980	2884.5	2895	2879	2847	2857.5	2845
14	3187	3183	-4	3102	3098	3100	2977	2973	2975	2864	2860	2867	2824	2820	2820
15	3195.5	3197	+1.5	3118.5	3120	3119	2987	2988.5	2988	2872	2873.5	2876	2831	2832.5	2830
R Q 16	3262	3262	0	3227	3227	3231	3081	3081	3082	2936	2936	2939			2895
17	3214.5	3213	-1.5	3121	3119.5	3120	2975	2973.5	2976	2837.5	2836	2842	2797	2795.5	2820
18	3215	3215	0	3153	3153	3154	3003.5	3003.5	3003	2868	2868	2870	2830	2830	2830
19	3217	3214	-3	3137.5	3134.5	3139	2990	2987	2991	2859	2856	2855	2805	2802	2819
20	3215	3215	0	3117	3117	3119	2971.5	2971.5	2973	2840	2840	2843	2808.5	2808.5	2812
21	3219	3217	-2	3103	3101	3100	3003	3001	3000	2897	2895	2897	2867	2865	
22	3227	3225	-2	3093	3091	3094	2993	2991	2993	2901	2899	2903	2876	2874	
23	3226	3225	-1	3081	3080	3081	2979	2978	2975	2891	2890	2893	2870	2869	
24	3234	3234	0	3113	3113	3112	3013	3013	3010	2917	2917	2918	2830	2830	
25	3231	3231	0	3129	3129	3127	3023	3023	3020	2914	2914	2925	2883	2883	
26	3223	3226	+3	3104.5	3107.5	3106	2999	3002	3000	2899.5	2902.5	2900	2863	2866	
B R 4	3299	3305	+6	3185	3191	3184	3060	3066	3055			2915			2870
7	3306	3307	+1	3250	3251	3255	3160	3161	3155	3031	3032	3035			2895
9	3298.5	3299	+0.5			3230			3145			3020	2981	2982	2970
10	3294.5	3294	-0.5	3223	3222.5	3225	3145	3049.5	3145	3017	3016.5	3105			2970
11	3303.5	3304	+0.5	3238	3238.5	3250	3159	3159.5	3165	3029	3029.5	3035	2974	2973.5	2990

TABLE 3-3

Contact Determinations from Electric (Potential) Log Curve

R N	General			Leduc Member			Ireton Member			Nisku Member			Calmar Member		
	R D L	T D	C F	R D	C D	C B D	R D	C D	C B D	R D	C D	C B D	R D	C D	C B D
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
I R 1	3187	3186	-1	3180	3179	3175	3082	3081	3085	2963	2962	2960	2909	2908	2920
2	3306	3310	+4	3167	3171	3165	3080	3084	3080	2962	2966	2962	2905	2909	2910
3	3254	3256	+2			3145	3002	3004	3000	2872	2874	2872	2826	2828	2820
4	3270	3279	+9			3157	3068	3071	3065	2942	2951	2943	2898	2898	2900
5	3208	3208	0	3046	3046	3044	2940	2940	2940	2815	2815	2820	2770	2770	2775
7	3090	3089	-1			3090	2979	2979	2980	2838	2837	2802	2798	2797	2755
8	3139	3139	0	3135	3135	3135	3006	3006	3010	2864	2864	2865	2817	2817	2820
9	3194	3196	+2	3187	3189	3187	3051	3053	3055	2912	2914	2910	2867	2869	2875
10	3164	3162	-2	3160	3162	3160	3023	3021	3025	2897	2895	2898	2854	2852	2860
11	3326	3325	-1	3133	3132	3131	3046	3045	3048	2909	2908	2907	2859	2858	2868
12	3250	3250	0	3204	3204	3201	3061	3061	3065	2925	2925	2923	2884	2884	2885
13	3176	3175	-1	3173	3172	3174	3037	3036	3037	2903	2902	2904	2856	2855	2855
I O 14	3243	3242	-1	3237	3236	3234	3125	3124	3125	2981	2980	2977	2941	2940	2940
16	3220	3222	+2	3214	3216	3213	3110	3113	3116	2959	2961	2959	2919	2921	2920
17	3177	3178	+1	3175	3176	3173	3030	3031	3080	2944	2945	2944	2903	2904	2902
18	3324	3328	+4	3169	3172	3165	3065	3069	3067	2931	2935	2931	2897	2901	2895
19	3347	3348	+1	3273	3274		3156	3157		3010	3011		2968	2969	
20	3181	3179	-2	3176	3174	3177	3032	3030	3083	2937	2935	2937	2897	2895	2897
I S 21	3142	3142	0	3132	3132	3133	3034	3034	3036	2957	2937	2938	2897	2897	2900
22	3296	3296	0	3099	3099	3133	2978	2978	3034	2870	2870	2927	2849	2849	2888
23	3264	3265	+1	3121	3122	3121	3011	3012	3010	2904	2905	2906	2873	2874	2875
24	3097	3099	+2	3079	3081	3102	2955	2957	2980	2889	2891	2865	2873	2875	
I A 25	3158	3158	0			3146	3053	3053	3050	2941	2941	2952	2903	2903	2900
26	3202	3202	0	3196	3196	3194	3034	3034	3030	2954	2954	2905	2914	2914	2860
27	3107	3108	+1			3116	3010	3011	3005	2890	2891	2890	2847	2848	2845
28	3095	3095	0	3093	3093	3093	2983	2983	2980	2889	2889		2856	2856	
29	3142	3141	-1			3061	3047	3047	3050	2954	2953	2964	2903	2902	2915
30	3166	3167	+1	3163	3164	3162	3069	3069	3068	2963	2964		2916	2917	2920
31	3108	3106	-2	3098	3096	3098	2972	2970	2975	2876	2874	2875	2815	2813	
32	3252	3253	+1	3069	3070	3068	2957	2958	2960	2666	2667	2860	2824	2825	
33	3208	3209	+1	3202	3203	3202	3051	3052	3053	2915	2916	2915	2871	2872	2874
34	3235	3234	-1	3231	3230	3230	3068	3067	3070	2944	2943	2945	2903	2902	2905
35	3209	3209	0	3203	3203	3203	3108	3108	3106	3016	3016	3015	2957	2957	2977
36	3092	3090	-2	3087	3085	3086	2968	2966	2970	2870	2868	2870	2828	2826	2830
37	3085	3084	-1	3083	3082	3082	2977	2976	2975	2879	2875	2878	2832	2831	2840
38	3104	3113	+9			3100	2971	2980	2970	2867	2876	2870	2822	2831	2820
39	3176	3176	0	3168	316	3167	3012	3012	3029	2906	2906	2905	2863	2863	2864
40	3137	3136	-1	3130	3135	3135	3008	3008	3005	2898	2897	2900	2855	2854	
I E 41	3144	3144	0				3061	3061	3063	2922	2922	2920	2878	2878	2880
42	3135	3135	0			3100	2993	2993	2995	2857	2857	2857	2815	2815	2820
44	3100	3100	0	3093	3095	3093	3006	3006	3010	2871	2871	2870	2826	2826	2825

TABLE 2-3 (Cont'd.)

Contact Determinations from Electric (Potential) Log Curve

R N	General			Leduc Member			Ireton Member			Nisku Member			Calmar Member		
	R D L	T D	C F	R D	C D	C B D	R D	C D	C B D	R D	C D	C B D	R D	C D	C B D
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
I E 45	3150	3148	-2				3059	3057		2925	2923		2880	2878	
46	3114	3113	-1	3110	3109	3108	3027	3026	3000	2891	2890	2890	2845	2844	2850
47	3139	3139	0	3134	3134	3133	3044	3044	3045	2911	2911	2910	2868	2868	2870
48	3211	3211	0	3201	3201	3203	3106	3106	3108	2966	2966	2967	2914	2914	2920
49	3151	3152	+1	3133	3134	3132	3028	3029	3030	2894	2895	2895	2850	2851	2850
50	3218	3219	+1	3213	3214	3214	3112	3113	3113	2972	2973	2972	2928	2929	2928
51	3172	3170	-2	3165	3163	3169	3069	3067	3072	2931	2929	2930	2888	2886	2889
53	3140	3142	+2	3137	3139	3136	3029	3031	3030	2890	2892	2890	2847	2849	2846
54	3180	3179	-1	3173	3172	3173	3079	3078	3083	2946	2945	2946	2900	2899	2900
55	3130	3137	+7	3175	3182	3175	3071	3078	3073	2931	2938	2931	2887	2895	2886
56	3336	3339	+3	3163	3166	3162	3060	3063	3063	2920	2923	2920	2876	2879	2876
57	3198	3195	-3	3192	3189	3192	3062	3059	3065	2917	2914	2915	2868	2865	2870
58	3155	3153	-2	3151	3149	3150	3040	3038	3040	2895	2898	2895	2852	2850	2860
R R 2	3185	3183	-2	3179	3177	3178	3045	3043	3045	2907	2905	2905			2855
3	3224	3225	+1	3213	3214	3213	3072	3073	3075	2929	2930	2928	2878	2879	2900
4	3218	3235	+17	3213	3230	3211	3067	3084	3065	2923	2940	2925	2880	2897	2880
R T 5	3097	3097	0	3091	3091	3089	2938	2938	2940	2807	2807	2818	2768	2763	2770
6	3126	3126	0	3115.5	3115.5	3114	2971.5	2971.5	2975	2856	2856	2848	2809	2809	2810
7	3146	3146	0	3095.5	3095.5	3093	2972	2972	2970	2861	2861	2862	2828	2828	2830
8	3117	3117	0	3110	3110	3106	2988	2988	2990	2866	2866	2867	2843	2843	2845
9	3039	3039	0	3033	3033	3030	2914	2914	2915	2805	2805	2805	2786	2786	2785
10	3037	3028	-9	3033	3024	3033	2910	2901	2910	2799	2790	2800	2774.5	2765.5	2775
11	3092	3093	+1	3088.5	3089.5	3086	2944	2945	2945	2815	2816	2818	2781	2782	2780
12	3080	3080	0	3073	3073		2925	2925		2794	2794		2761	2761	
13	3105	3106	+1	3101	3102	3100	2979	2980	2980	2885	2886	2879	2847	2848	2845
14	3109	3112	+3	3102	3105	3100	2975	2978	2975	2860	2863	2867	2820.5	2823.5	2820
15	3124	3124	0	3021	3021	3119	2987	2987	2988	2869	2869	2876	2830	2830	2830
R Q 16	3238	3238	0	3233	3233	3231	3080	3080	3082	2939	2939	2939	2894	2894	2895
17	3129	3129	0	3122.5	3122.5	3120	2973	2973	2976	2843	2843	2842	2814	2814	2820
18	3160	3160	0	3155.5	3155.5	3154	3002.5	3002.5	3003	2869	2869	2870	2822	2822	2830
19	3145	3145	0	3140	3140	3139	2988	2988	2991	2859	2859	2855	2815.5	2815.5	2819
20	3130	3130	0	3120.5	3120.5	3119	2972	2972	2973	2842.5	2842.5	2843	2810	2810	2812
21	3109	3110	+1	3105	3106	3100	3002	3003	3000	2896	2897	2897	2861	2862	
22	3102	3100	-2	3093	3091	3094	2992	2990	2993	2907	2905	2903	2877	2875	
23	3086	3086	0	3081	3081	3081	2973	2978	2975	2892	2892	2893	2870	2870	
24	3119	3118	-1	3011	3010	3112	3009.5	3008.5	3010	2919.5	2918.5	2918	2880	2879	
25	3150	3150	0	3127	3127	3127	3021	3021	3020	2926	2926	2925	2889.5	2889.5	
26	3114	3113	-1	3105	3104	3106	2997	2996	3000	2902	2901	2900	2866.5	2865.5	
E R 4	3183	3189	+1	3183	3184	3184	3057	3058	3055	2918	2919	2915	2870	2871	2870
7	3258	3259	+1	3249	3250	3255	3162	3163	3155	3033	3034	3035	2983	2984	2995
9	3236	3236	0	3227	3227	3230	3141	3141	3145	3014	3014	3020	2967	2967	2970
10	3234	3231	-3	3227	3224	3225	3144	3141	3145	3018	3015	3005	2972	2969	2970
11	3252	3252	0	3245	3245	3250	3166	3166	3165	3036	3036	3055	2988	2988	2990

TABLE 2-4

Comparisons of Readings Taken From Tables 2-2 and 2-3

W R N	Leduc Member				Ireton Member				Nisku Member				Calmar Member			
	Ru:Eu	Rc:Ec	Rc:CBD	Ec:CBD	Ru:Eu	Rc:Ec	Rc:CBD	Ec:CBD	Ru:Eu	Rc:Ec	Rc:CBD	Ec:CBD	Ru:Eu	Rc:Ec	Rc:CBD	Ec:CBD
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
I R 1	+2	+4	0	-4	-5	-3	+1	+4	+3	+5	+3	-2	+1	+3	+5	+12
2	+4	+2	-4	-6	+2	0	-4	-4	+4	+2	-2	-4	+3	+1	+2	+1
3			+6.5		-1	+0.5	-3.5	-4				-2				-8
4			+17 *		-2	+3	-3	-6	+2	+7	-1	-8	+1	-3	-1	+2
5	+2	+2.5	+0.5	-2	-3	-2.5	-2.5	0	-1	-0.5	+4.5	+5	-4	-3.5	+1.5	+5
7			+2		+2	+3	+4	+1	+4 *	+3 *	-32 *	-35 *	+28 *	+27 *	+5 *	-42 *
8	0	-1	-1	0	-2	-3	+1	+4	0	-1	0	+1	-1	-2	+1	+3
9	+1	+3	+1	-2	-3	0	+2	+2				-4				+6
10	-1	+2	0	-2	-2	-3	+1	+4				+3				+8
11	+4	+3	+2	-1	+1	0	+3	+3	+4	+3	+2	-1	+4	+3	+13	+10
12	+4	+4.5	+1.5	-3	-4	-3.5	+0.5	+4	+2	+2.5	+0.5	-2	+18 *	+18.5*	+19.5*	+1 *
13	-2	+1.5	+3.5	+2	-4	-0.5	+0.5	+1	-2	+1.5	+3.5	+2	-3	+0.5	+0.5	0
I O 14	+19 *	+15 *	+14 *	-2 *	+2	-1	0	+1	+2	-1	-4	-3	0	-3	-3	0
16	+1	+2	-1	-3	0	+1	-1	-2	0	+1	-1	-2	0	+1	0	-1
17	+2	+8.5	+5.5	-3	+1	+7.5	+6.5	-1	+2	+8.5	+7.5	-1	0	+6.5	+4.5	-2
18	+9	+9	+2	-7	-2	-2	-4	-2	+1	+1	-3	-4	+44 *	+44 *	+38 *	-6 *
19	+3	+5			-1	+1										
20	0	0	+3	+3	-3	-3	0	+3	0	0	+2	+2	+2	+2	+4	+2
I S 21	-6	-4.5	-3.5	+1	-1	+0.5	+2.5	+2	+3	+4.5	+5.5	+1	+2	+3.5	-3.5	-7
22	+5 *	+4 *	+43 *	+39 *	+1 *	0 *	+56 *	+56 *	+9 *	+8 *	+65 *	+57 *	+2	+1	+40 *	+39 *
23	-1	-0.5	-1.5	-1	-2	-1.5	-3.5	-2	-3	-2.5	-1.5	+1	0	+0.5	+1.5	+1
24	-1 *	+3 *	+24 *	+21 *	-4 *	0 *	+23 *	+23 *	-4 *	0 *	-26 *	-26 *	-2	+2		
I A 25			0		-1	0	-3	-3	-7	-6	+5	+11	-2	-1	-4	-3
26	+2	+0.5	-1.5	-2	+5	+3.5	-0.5	-4	+5 *	+3.5*	-45.5*	-49 *	+5 *	+3.5*	-50.5*	-54 *
27			-3.5		-3	-2.5	-8.5	-6	-2	-1.5	-2.5	-1	-1	-0.5	-3.5	-3
28	0	-2	-2	0	-3	-5	-8	-3	0	-2			0	-2		
29			+3.5		+3	+1.5	+4.5	+3	+4	+2.5	+13.5	+11	+9 *	+7.5*	+20.5*	+13 *
30	0	+0.5	-1.5	-2	0	+0.5	-0.5	-1	+1	+1.5			+2	+2.5	+5.5	+3
31			-0.5	+2	-2	-4.5	+0.5	+5				+1				
32	-1	-1	-3	-2	-2	-2	0	+2	+7	+7	0	-7				
33	0	0	-1	-1	-3	-3	-2	+1	0	0	-1	-1	+8	+8	+10	+2
34	+6	+2.5	+2.5	0	-3	-0.5	+2.5	+3	+5	+1.5	+3.5	+2	+18 *	+14.5*	+17.5*	+3 *
35	+3	+1.5	+1.5	0	+1	-0.5	-2.5	-2	+6	+4.5	+3.5	-1	+1 *	-0.5*	+19.5*	+20 *
36	+1	+1	0	-1	-2	-4	0	+4	+8	+6	+8	+2	0	-2	+2	+4
37	+2	+1	+1	0	+1	0	-1	-1	+2	+1	+4	+3	-4	-5	+4	+9
38			+2		-1	+9	-1	-10	+7 *	+17 *	+11 *	-6 *	-2	+8	-3	-11
39	+1	+1	0	-1	-17 *	-17 *	-1 *	16 *	+1	+1	0	-1	-3	-3	-2	+1
40	+1	-2	-2	0	-1	-4	-1	+3	+4	+1	+4	+3	0	-3		
I E 41					-1	+1.5	+3.5	+2	+1	+3.5	+1.5	-2	0	+2.5	+4.5	+2
42			-0.5		0	-1.5	+0.5	+2	+3	+1.5	+1.5	0	+11	+9.5	+14.5	+5
44	+2	+2.5	+2.5	0	-3	-2.5	+1.5	+4	-2	-1.5	-2.5	0	-4	-3.5	-4.5	-1
45					-1	-4			+1	-2	+5	-2	-2	-5		
46	+4	+5	+4	-1	-2	-1	+3	+4	+4	+5	+1.5	-1	-4	-3	+3	+6

TABLE 2-4 (Cont'd.)

Comparisons of Readings Taken From Tables 2-2 and 2-3

W R N	Leduc Member				Ireton Member				Nisku Member				Calmar Member			
	Ru:Eu	Rc:Ec	Rc:CBD	Ec:CBD	Ru:Eu	Rc:Ec	Rc:CBD	Ec:CBD	Ru:Eu	Rc:Ec	Rc:CBD	Ec:CBD	Ru:Eu	Rc:Ec	Rc:CBD	Ec:CBD
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
I E 47	+6	+5.5	+4.5	-1	+1	+0.5	+1.5	+1	+3	+2.5	+3	0	-2	+1.5	+3.5	+2
48	0	+2	+4	+2	-6	-4	-2	+2	0 *	+2 *	+26 *	0 *	-3	-1	+5	+6
49	0	+5	+3	-2	-2	+3	+4	+1	+21 *	+26 *	+26 *	-0 *	+9	+14	+13	-1
50	+3	+3	+3	0				0				-1				-1
51	-4	-6	0	+6	-1	-3	+2	+5	+3	+1	+2	+1	-2	-4	-1	+3
53	+2	+3.5	+0.5	-3	-1	+2.5	+1.5	-1	-1	+0.5	-11.5	-2	0	+1.5	-1.5	-3
54	-3	+5.5	+6.5	+1	-7	+1.5	+6.5	+5	0	+8.5	+9.5	+1	-2	+6.5	-2.5	-9
55	-2	+7.5	+0.5	-7	-6	+3.5	-1.5	-5	-6	+3.5	-3.5	-7	-3	+6.5	-1.5	-9
56	0	+0.5	-3.5	-4	-4	-3.5	-3.5	0	+4	+4.5	-1.5	-3	-1	+1.5	-1.5	-3
57	0	-0.5	+2.5	+3	-2	-2.5	+3.5	+6	+2	+1.5	2.5	+1	0	-5.5	-0.5	+5
58	+3	-1	0	+1	-1	-5	-3	+2	+1	-3	-1	+2	+2	-2	+8	+10
R R 1			-0.5				0				-8					
2	-1	-1.5	-0.5	+1	-4	-4.5	-2.5	+2	+8	+7.5	-2.5	0			-8.5	
3	-4	+1	0	-1	-5	0	+2	+2	-3	+2	0	-2	+6 *	+11 *	+32 *	+21 *
4	-1 *	+16.5*	-2.5*	-19 *	-4 *	+13.5*	-5.5*	-19 *	-2 *	+15.5*	+0.5*	-15 *	+4.5*	+22 *	+5 *	-17 *
R T 5	+3.5	+3	+1	-2	-1	-1.5	+0.5	+2	-2	-2.5	+8.5	+11	-2	-2.5	-0.5	+2
6	+2.5	+2.5	+1	-1.5	-1.5	-1.5	+2	+3.5	+9	+9	+1	-8	-1.5	-1.5	-0.5	+1
7	+0.5*	+23.5*	+21 *	-2.5*	-1 *	+22 *	+20 *	-2 *	-2 *	+21 *	+22 *	+1 *	0 *	+23 *	+25 *	+2 *
8	+2.5	-5.5	-9.5	-4	-3	-11	-9	+2	-2	-10	+9	+1	+9	+1	+3	+2
9	+5	+8.5	+5.5	-3	+2	+5.5	+6.5	+1	+4	+7.5	+7.5	0	+23 *	+26.5*	+25.5*	-1 *
10	0	-10	-1	+9	-5	-15	-6	+9	+1	-9	+1	+10	+1.5	-8.5	+1	+9.5
11	+2.5	0	-3.5	-3.5	-2	-4.5	-4.5	0	-1	-3.5	-1.5	+2	0	-2.5	-4.5	-2
12	+2	+2			-5	-5			-1	-1			-1	-1		
13	+1	-8.5	-10.5	-2	13	+3.5	+3.5	0	+0.5*	-9 *	-16 *	-7 *	0	-9.5	-12.5	-3
14	0	+7	+2	-5	-2	+5	+2	-3	-4	+3	+7	+4	-3.5	+3.5	0	-3.5
15	+2.5	+1	-1	-2	0	-1.5	-0.5	+1	-3	-4.5	+2.5	+7	-1	-2.5	-2.5	0
R Q 16	+6	+6	+4	-2	-1	-1	+1	+2	+3	+3	+3	0				+1
17	+1.5	+3	+0.5	-2.5	-2	-0.5	+2.5	+3	+5.5	+7	+6	-1	+17 *	+18.5*	+24.5*	+6 *
18	+2.5	+2.5	+1	-1.5	-1	-1	-0.5	+0.5	+1	+1	+2	+1	-8	-8	0	+8
19	+2.5	+5.5	+4.5	-1	-2	+1	+4	+3	0	+3	-1	-4	+10.5*	+13.5*	+17 *	+3.5*
20	+3.5	+3.5	+2	-1.5	+0.5	+0.5	+1.5	+1	+2.5	+2.5	+3	+0.5	+1.5	+1.5	+3.5	+2
21	+2	+5	-1	-6	-1	+2	-1	-3	-1	+2	+2	0	-6	-3		
22	0	0	+3	+3	-1	-1	+2	+3	+6	+6	+4	-2	+1	+1		
23	0	+1	+1	0	-1	0	-3	-3	+1	+2	+3	+1	0	+1		
24	-2	-3	-1	+2	-3.5	-4.5	-3	+1.5	+2.5	+1.5	+1	-0.5	0	-1		
25	-2	-2	-2	0	-2	-2	-3	-1	+12	+12	+11	-1	+6.5	+6.5		
26	+0.5	-3.5	-1.5	+2	-2	-6	-2	+4	+2.5	-1.5	-2.5	-1	+3.5	-0.5		
B R 4	-2	-7	-7	0	-3	-8	-11	-3				-4				-1
7	-1	-1	+4	+5	+2	+2	-6	-8	+2	+2	+3	+1	+2	+2		+11
9				+3				+4				+6			-12	+3
10	+4	+1.5	+2.5	+1	-1	-3.5	-4.5	+4	+1 *	-1.5*	-11.5*	-10 *	-2	-4.5		+1
11	+7	+6.5	+11.5	+5	+7	+6.5	+5.5	-1	+7	+6.5	+5.5	-1	+3 *	+2.5*	+16.5*	+2 *
SD1	2.9	4.1	3.4	2.7	3.1	4.0	3.6	2.5	3.8	4.4	4.7	3.8	3.5	4.4	5.5	5.2
N R	67	67	74	67	77	77	75	74	65	65	65	69	59	59	47	54
SD2	3.7	5.4	4.8	3.5	3.6	5.0	4.2	3.8	4.5	6.3	7.3	4.3	8.3	Too large to be significant.		
N R	72	72	78	70	82	82	78	77	77	77	70	76	74			

APPENDIX 2-B

INDEX OF WELLS

Reference Number	Well Name and Number		Lsd	Sec	Twp	Rge W4M
IR 1	Imperial Redwater	3	1	20	57	21
IR 2		49	11	20	57	21
IR 3		53	11	22	57	21
IR 4		58	3	29	57	21
IR 5		69	9	29	57	21
IR 7		72	12	28	57	21
IR 8		76	9	32	57	21
IR 9		81	9	28	57	21
IR 10		86	9	22	57	21
IR 11		95	11	33	57	21
IR 12		97	1	33	57	21
IR 13		105	3	27	57	21
IO 14	Imperial Opal	1	1	22	58	22
IO 16		9	1	21	58	22
IO 17		11	3	21	58	22
IO 18		18	10	21	58	22
IO 19		25	11	22	58	22
IO 20		27	1	20	58	22
IS 21	Imp.-HB Simmons	3	3	26	56	21
IS 22	Imperial Simmons	5	11	25	56	21
IS 23		15	9	26	56	21
IS 24		21	9	24	56	21
IA 25	Imperial Amelia	13	3	10	57	21
IA 26		20	14	14	57	21
IA 27		22	11	10	57	21
IA 28		27	1	10	57	21
IA 29		36	1	3	57	21
IA 30		38	3	3	57	21
IA 31		40	9	2	57	21
IA 32		42	11	2	57	21
IA 33		46	1	14	57	21
IA 34		50	9	14	57	21
IA 35		59	1	4	57	21
IA 36		61	1	2	57	21
IA 37		63	3	2	57	21
IA 38		71	3	1	57	21
IA 39		74	1	11	57	21
IA 40		84	11	11	57	21
IE 41	Imperial Egremont	14	3	11	57	21
IE 42		17	9	6	58	21

Reference Number	Well Name and Number		Lsd	Sec	Twp	Rge W4M
				Location		
IE 44	Imperial Egremont	32	11	1	58	22
IE 45		35	11	6	58	21
IE 46		37	1	11	58	22
IE 47		38	2	11	58	22
IE 48		40	10	11	58	22
IE 49		41	13	6	58	21
IE 50		47	9	11	58	22
IE 51		54	1	14	58	22
IE 53		61	1	12	58	22
IE 54		63	3	12	58	22
IE 55		69	9	12	58	22
IE 56		71	11	12	58	22
IE 57		77	1	7	58	21
IE 58		79	3	7	58	21
RR 1	Royalite Redwater	6-15	6	15	57	21
RR 2		18-5	2	5	58	21
RR 3		19-5	7	5	58	21
RR 4		21-5	8	5	58	21
RT 5	Royalite Triad	1-1	1	1	57	21
RT 6		2-1	2	1	57	21
RT 7		3-36	3	36	56	21
RT 8		4-36	4	36	56	21
RT 9		5-36	5	36	56	21
RT 10		6-36	6	36	56	21
RT 11		7-1	7	1	57	21
RT 12		8-1	8	1	57	21
RT 13		12-36	12	36	56	21
RT 14		13-36	13	36	56	21
RT 15		14-36	14	36	56	21
RQ 16	Royalite Quadra	4-4	4	4	58	21
RQ 17		3-31	3	31	56	20
RQ 18		4-31	4	31	56	20
RQ 19		5-31	5	31	56	20
RQ 20		6-31	6	31	56	20
RQ 21		4-35	4	35	56	21
RQ 22		6-35	6	35	56	21
RQ 23		11-35	11	35	56	21
RQ 24		12-35	12	35	56	21
RQ 25		13-35	13	35	56	21
RQ 26		14-35	14	35	56	21
BR 4	B.A. Redwater	6-5	6	5	58	21
BR 7	B.A.-HB Redwater	3-30	3	30	57	21
BR 9		6-30	6	30	57	21
BR 10		11-30	11	30	57	21
BR 11		12-30	12	30	57	21

PART THREE

THE APPLICATION OF THE GAMMA RAY LOG IN CORRELATION PROBLEMS

Introduction

Radioactivity logs, being a relatively new development in geological investigations, have not received much attention in correlation work. The principal reason for this is that electric logs have been on the scene for many more years and have been used extensively by the oil industry. As a result of this use, most geologists in the petroleum field are familiar with the logs and can interpret them without undue difficulty. Their use in correlation problems has long been known, and is pointed out in most of the literature. It is suggested here that the gamma ray log, properly interpreted, may prove to be an even more valuable tool in the problems of short and long range stratigraphic correlation in Western Canada. This is especially so in the Paleozoic formations.

Short Range Correlation

Figure 3-1 (in pocket) shows an example of short range correlation within one field. The distance represented between the end wells is 15.1 miles. As can be seen, the contacts of the various

horizons are clearly discernible throughout the length of the field. Perhaps more important than showing the lateral extent of formations, the gamma ray log shows changes of lithology within a formation quite clearly. It is in this respect that the radioactivity log is of more value than the electric log.

Take, for example, the Nisku Member as shown in the section. Near the top of the member are two dolomitic silt bands which produce prominent deflections in the logs of most of the wells. The upper 8 foot band, occurring about 10 feet below the top is quite variable, disappearing in the middle of the field. The lower band, occurring about 20 feet below the top is about 5-10 feet in thickness. This is an extensive horizon although varying in thickness. It has also been found in the Leduc field.

In the Ireton Member one may trace the lensing in and out of the calcareous or dolomitic phases of the shale. Thus, in Imperial Opal #18 there is a decidedly dolomitic stringer near the top of the member. This phase may be traced through Opal #9 and Egremont #40, but appears to die out after this. Other similar changes in lithology can be traced down the length of the field.

The changes in the lithology of the Calmar Member are also shown quite clearly.

From the interpretation of these litho-facies changes, a picture of the sedimentation of an area may be built up, if sufficient sections are made.

Long Range Correlation

Figure 3-2 (in pocket) is an example of the application of gamma ray logs to long range correlation. The three northerly wells are in the Opal, Redwater and Simmons sectors of the Red-water oil field. Imperial Stony Plain No. 1 is a wildcat well drilled southwest of Edmonton on the southern extremity of what is now called the Acheson reef. The three southerly wells are in the Golden Spike, Woodbend, and Leduc sectors of the Leduc oil field. The total distance measured in a straight northeast-southwest line between the two extrem-ities is 54 miles. The location map on the figure shows the wide separation of the two groups of wells.

The correlation of the Upper Devonian formational members under discussion between the two areas is clearly shown by the gamma ray logs.

Again, the lithologic variation within

formation members is illustrated by the logs. Perhaps the most striking example of this is in the Ireton Member. In the Redwater area the Nisku-Ireton contact is fairly well defined both by the log, and in the cores.

The transition zone between the two formations is small and in many cores the contact is visible to the naked eye. In the Leduc area, however, the Nisku-Ireton contact is not well defined. The transition zone is broad, often up to 15 feet. The contact is picked from cores at the first appearance of argillaceous material in the basal Nisku dolomite. Often there are pure or almost pure dolomite bands up to 8 feet thick below this point in the cores. The Ireton itself in the Leduc area is a very impure shale, having calcareous and dolomitic bands, partings and fractures. The basal portion, however, is usually a fairly clean, slightly calcareous shale, and the contact with the Leduc Member is sharp and easily seen in core and chip samples.

The gamma ray logs of the Leduc area wells show this gradational nature of the member very clearly. The gradual increase in argillaceous material is well defined in the progressive increase in the logs' radiation intensities, culminating in

the relatively pure shale. The Ireton-Leduc contact is also shown to be sharp.

The silt band within the Nisku Member, mentioned previously in connection with the Redwater field, is also visible in logs of the Leduc area wells. The band is not developed in the Stony Plain well, is poorly developed in the Golden Spike sector, is fairly well developed in the Woodbend area, and is especially well developed in the Leduc sector. It is not so well defined in the southern areas, however, as it is in the Redwater field.

Lithologic Interpretation of Gamma Ray Logs

The gamma ray log does not, according to the literature, distinguish between limestone and dolomite when both are pure. It is very seldom, however, that the pure material is encountered in the field. As shown in Figure 3-2, the gamma ray log will distinguish between a limestone and a dolomite formation. If one examines the logs of the three Redwater wells, one will see that the dolomite of the Nisku Member is more radioactive than the limestone of the Leduc member.

In the Leduc sector of the southern area,

both these formations are dolomite, or extremely dolomitic, so the difference in the gamma ray deflection does not appear on the log. The Golden Spike reef is limstone as at Redwater, and the Nisku is again more radioactive than the Leduc, although the difference in deflection is not so prominent here.

Although no attempt is made to show structure in Figure 3-2, the well spacing and sea level datum being ignored, it is obvious that the section thickens to the south and west. Golden Spike No. 5, the well furthest west, shows the greatest thicknesses of Nisku, Ireton and Calmar, of all the wells shown.

Summary and Conclusions

From the foregoing discussion one must conclude that the gamma ray log can be extremely valuable in both short and long range correlation work. Within a limited area, such as an oil field, they can be used to build up a very complete picture of the lithologic changes within formational units. From a study of these changes the sedimentation of an area may be worked out in detail.

Over greater distances formations can be correlated by means of the gamma ray log. If sufficient numbers of logs are available, the

sedimentation of larger areas may be studied. Even without detailed log coverage the lithologic changes of a large area can be traced, and from this knowledge of formation character may be increased.

With sufficient experience in interpreting the logs, the actual lithology of the formations can be accurately and quickly described without the benefit of core or bit cutting samples.

PART FOUR

NEUTRON WELL LOGGING

Introduction

The primary topic of this thesis is the natural radioactivity of sediments and its response on the gamma ray log. The writer, however, believes some mention should be made of the artificially induced radioactivity, and of its application to oil field porosity investigation. The process is known as neutron logging.

Instrumentation

The neutron curve is obtained through the use of an instrument very similar to that described for the gamma ray curve. The ionization chamber, however, is shortened from three feet to nine inches in length, and an appropriately shielded radium-beryllium neutron source is placed beneath the chamber, (4). Neutrons from the source bombard the earth material immediately surrounding the well bore, and the effect of this bombardment is measured by the ionization chamber. The source is of sufficient strength so that the gamma rays it induces in the rocks are of greater intensity than the natural gamma rays being emitted from the formations due to their radioactive elements. This

permits the measurement of the induced radiations without interference from the weaker natural ones. The shortening of the ionization chamber assists this by making it less sensitive to the rocks' natural radioactivity.

Theory of Neutron Logging

The development of neutron logging is based on the theory that neutrons are present in the atomic nuclei of all elements except hydrogen. The neutrons generated by the radium-beryllium source have very high original velocities and are called fast neutrons. In the strata surrounding the well bore they may be considered as undergoing two processes, reduction in velocity, and capture. Many elements have the ability to capture neutrons. In the capture process a neutron is taken into an atomic nucleus and, in the energy rebalance, bursts of gamma radiation may be emitted. It is these artificially stimulated gamma rays which are measured by the ionization chamber of the neutron instrument.

Since they carry no electrical charge, neutrons will collide readily with atomic nuclei in their paths. As a result of these collisions their velocity is reduced. The hydrogen nucleus

has a mass closely approximating that of the neutron, so hydrogen is the most important factor in reducing its velocity. Where hydrogen exists in the formation, the neutrons are slowed up near the source. This greatly reduces the number of neutrons available for capture near the ionization chamber. The resultant decrease in the gamma rays produced by the rocks is recorded by the ionization chamber. The neutron log might, therefore, be thought of as a log of the hydrogen content of rocks, as it has been shown (4) that the hydrogen effect controls the outline of the log curve. It will be noted that reference has been made only to hydrogen, and nothing has been said about its manner of occurrence. It makes no difference whether the hydrogen is combined with carbon as oil, with oxygen as water in a brine filling the rock pores, or whether it is present in absorbed water in a shale, or chemically combined water in limonite or gypsum. What is recognized is solely the effect of the hydrogen itself.

Since the hydrogen is almost always in fluids, the neutron log is a measurement of the amount of fluid surrounding the instrument. The fluid may be considered as being of two types:

that contained within the borehole, and the fluid present in any form within the formations.

The amount of borehole fluid surrounding the instrument normally remains constant, except at points such as the change in bore hole diameter and fluid level. It therefore has a negligible influence on the formation fluid's response of the neutron curve.

The formation fluid exerts the greatest influence on the neutron log. The behavior of the curve is such that the greater the amount of fluid, the lower the intensity of the curve. Thus the neutron log reflects the porosities of fluid-filled rocks, and not their permeabilities.

Shales, in general, contain the greatest amount of total fluid, and therefore give the lowest intensity values. Non productive limestones and dolomites contain very little, if any, fluid, and therefore record the highest radiation intensities.

Porosity Evaluations

Quantitative porosity evaluation of the neutron curve is a relatively recent development initiated in 1949. Before this, the curve had been

used purely as a qualitative indication of the presence of fluid. The procedure used in developing the quantitative porosity determinations is relatively new, the study having been initiated between 1945 and 1949. The general procedure used is the same in most cases; however the methods and scales developed are confined to the area for which the work is done. Thus evaluation scales have been worked out for West Texas (2), Louisiana (3), and the Redwater Oil Field of Alberta.

Porosity Evaluation at Redwater:

The method of porosity evaluation outlined below has been worked out for the Redwater Oil Field, (7). The writer understands that some modifications have been evolved since it appeared, but as yet these have not been published.

The evaluation procedure is based on two concepts:

1. The neutron curve response is a function of formation fluid content.

2. The formation fluid content is a function of porosity.

The validity of these concepts has been demonstrated in the curve evaluation procedure of other areas, (3).

The first step in the procedure is the determining of a base line on the log which is constant throughout the field. From this line all the other measurements are made. It has been found that the minimum values of the Ireton curve response are sufficiently constant to provide a reference. A vertical line through these points is projected down through the producing horizon (the Leduc Member) and is used as the reference line on which to base the evaluation scale.

The basic neutron evaluation scale is derived by using the figures obtained from a cored well on which a neutron log has been run. The percentage porosity of the core, obtained by core analyses, and averaged over two foot intervals, is plotted against the horizontal movement of the neutron curve pen, divided into suitable units. In Redwater the units chosen are inches of pen travel. The resultant graph is a smooth symmetrical curve with the majority of points falling right on the line. The maximum and minimum porosity values found for the initial well were 19 and 1.5 per cent, and figures beyond this range must be obtained by extrapolating the curve. The porosity evaluation scale is derived directly from the above graph by reading the percentage porosity

values at points on the curve established by intersecting lines drawn from the units of pen travel.

The scale has been used to check the porosities of many wells, the cores of which have been subsequently analysed. It has been found to be within 0.6 to 1 per cent of the values obtained by core analyses.

The authors of the scale state that, with certain limitations, the method may be applied to any field. This is not proved as yet; however it is very successful in the Redwater field, and has been adopted by many companies.

BIBLIOGRAPHY

1. Barcklow, J.C.; (1945): Better Interpretation of Neutron Curves; The Oil Weekly, Aug. 20.

2. Bush, R.E.; (1950): Porosities Can be Obtained from Radioactivity Logs in West Texas; The Oil and Gas Journal, April 27.

3. Bush, R.E. and Mardock, E.S.; (1950): Some Preliminary Investigations of Quantitative Interpretations of Radioactivity Logs; Jour. Pet. Tech., Vol. 189.

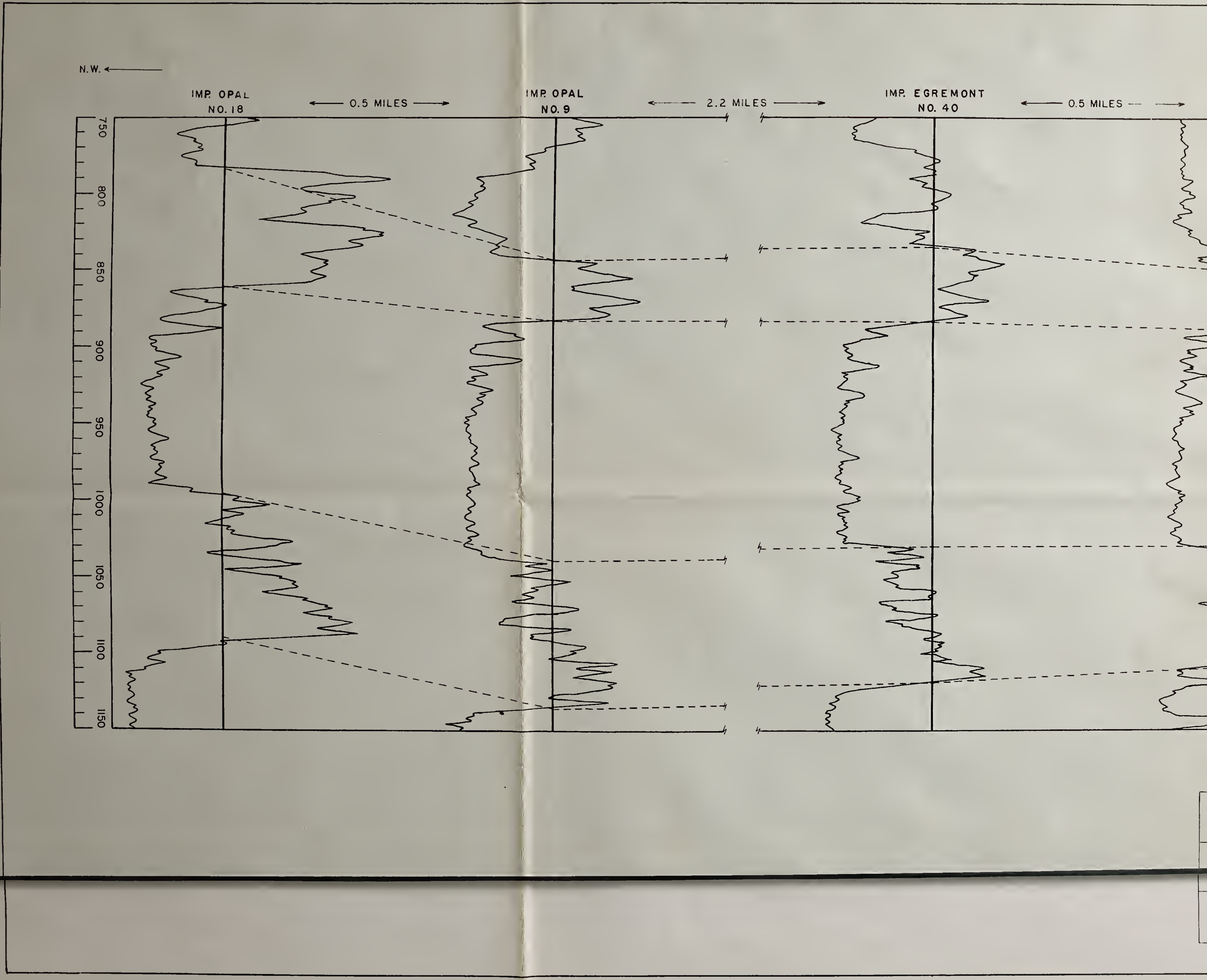
4. Fearon, R.E.; (1945): Radioactivity Well Logging; The Oil Weekly, July.

5. Jackson, W.J. and Campbell, J.L.C.; (1946): Some Practical Aspects of Radioactivity Well Logging; Trans. A.I.M.E., Vol. 165.

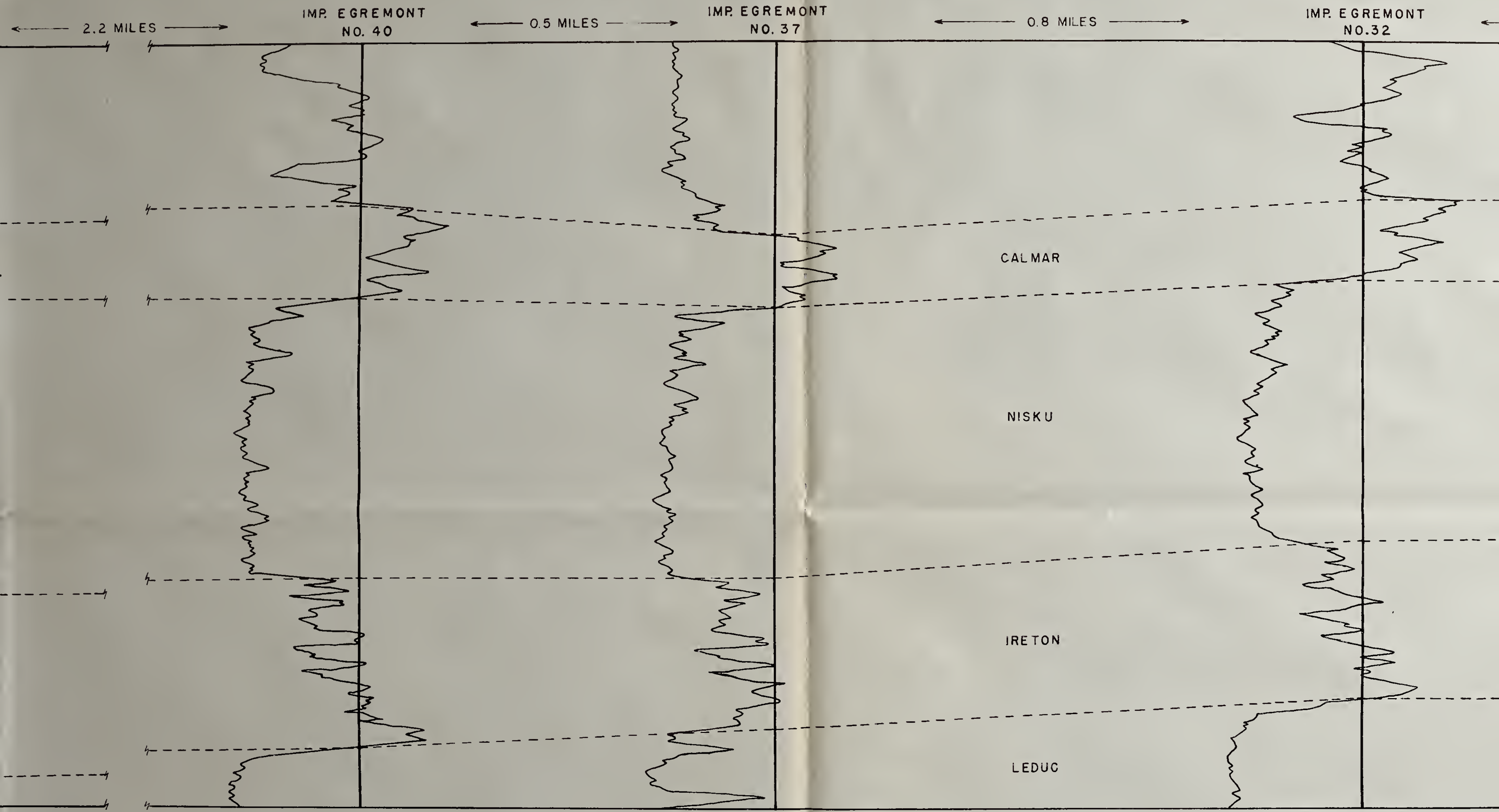
6. Long, W.D.; (1950): Theory of Radioactivity Well Logging and Its Usage in Western Canada; Can. Oil and Gas Industries, July.

7. McKay, J.R. and Henley, J.; (1950): A Practical Evaluation of the Neutron Log for Canadian Oil Fields; Can. Oil and Gas Industries, July.

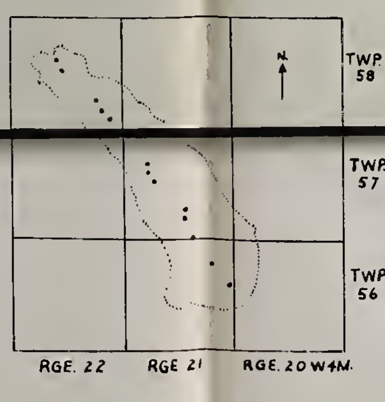
8. Mercier, V.J.; (1946): Radioactivity Well Logs; The Oil Weekly, Oct. 14,21.



N.W.
IMP. OPAL NO. 18
0.5 MILES
IMP. OPAL NO. 9
2.2 MILES
IMP. EGREMONT NO. 40
0.5 MILES
750
800
850
900
950
1000
1050
1100
1150



LOCATION MAP
OF WELLS USED



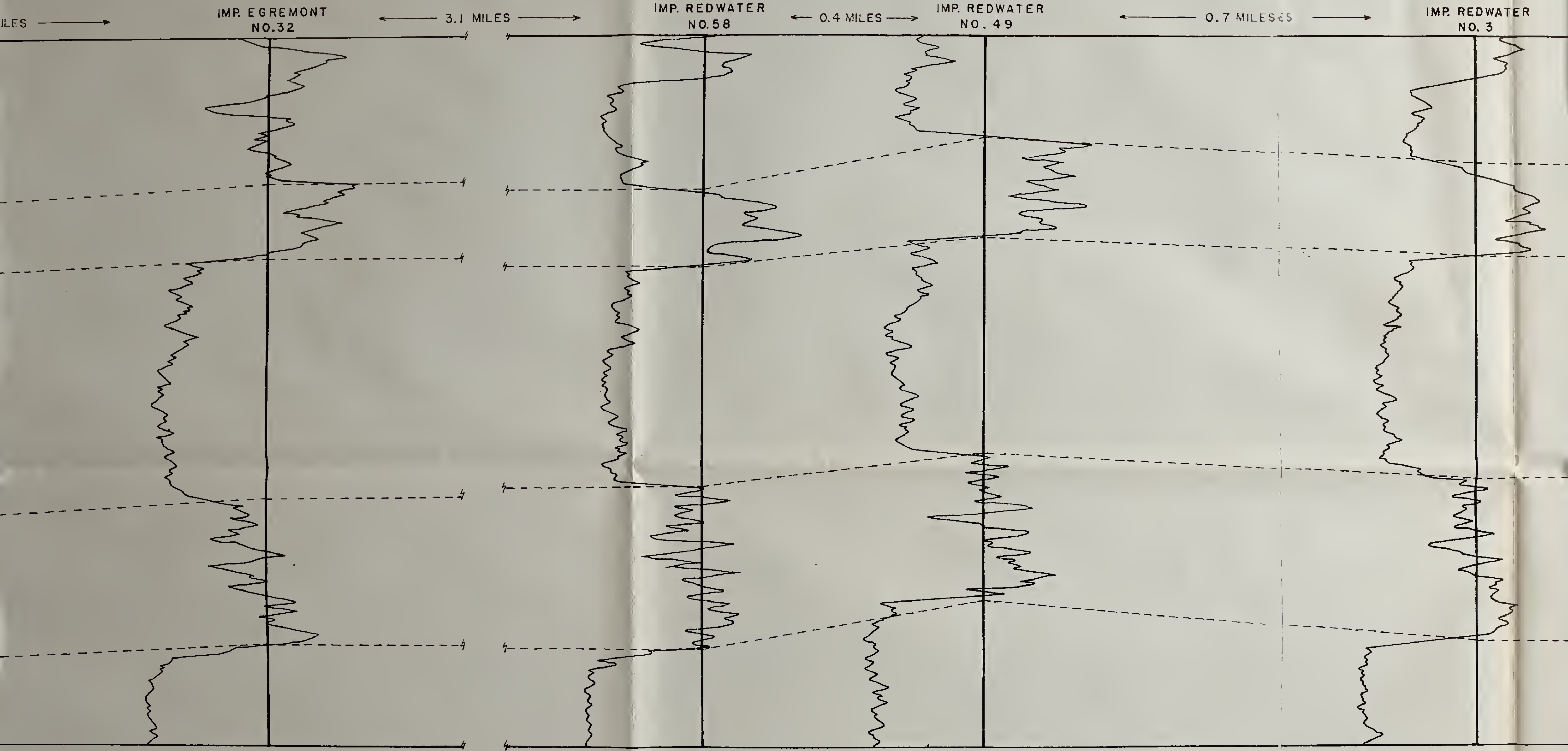
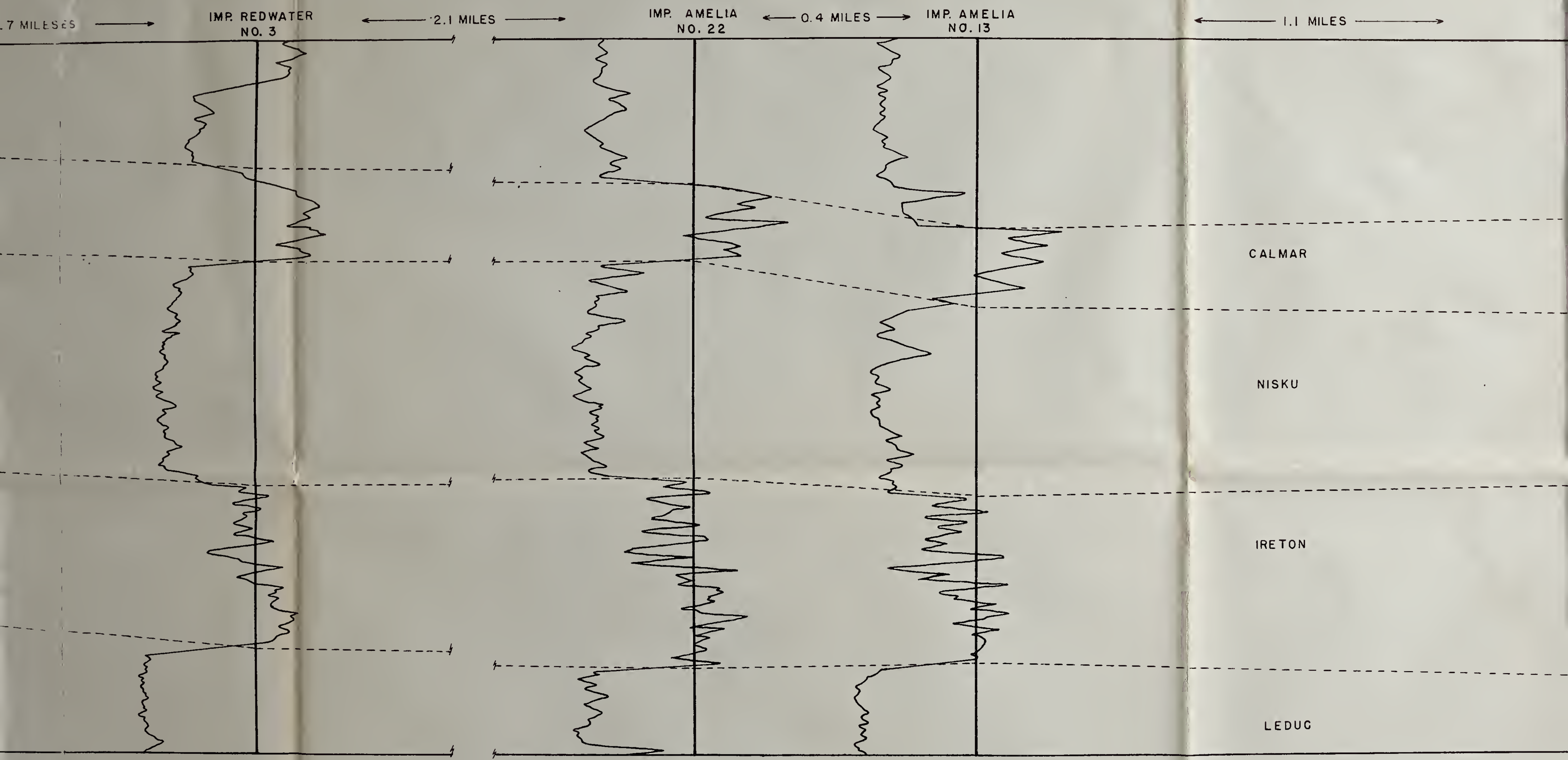


FIGURE 3-1

LONGITUDINAL RADIOACTIVITY SECTION

OF

REDWATER OIL FIELD



DATA

HORIZONTAL SCALE: 1 INCH = 660 FEET

VERTICAL SCALE: 1 INCH = 50 FEET

DATUM MEAN SEA LEVEL

NOTE: ALL ELEVATIONS ARE SUB-SEA

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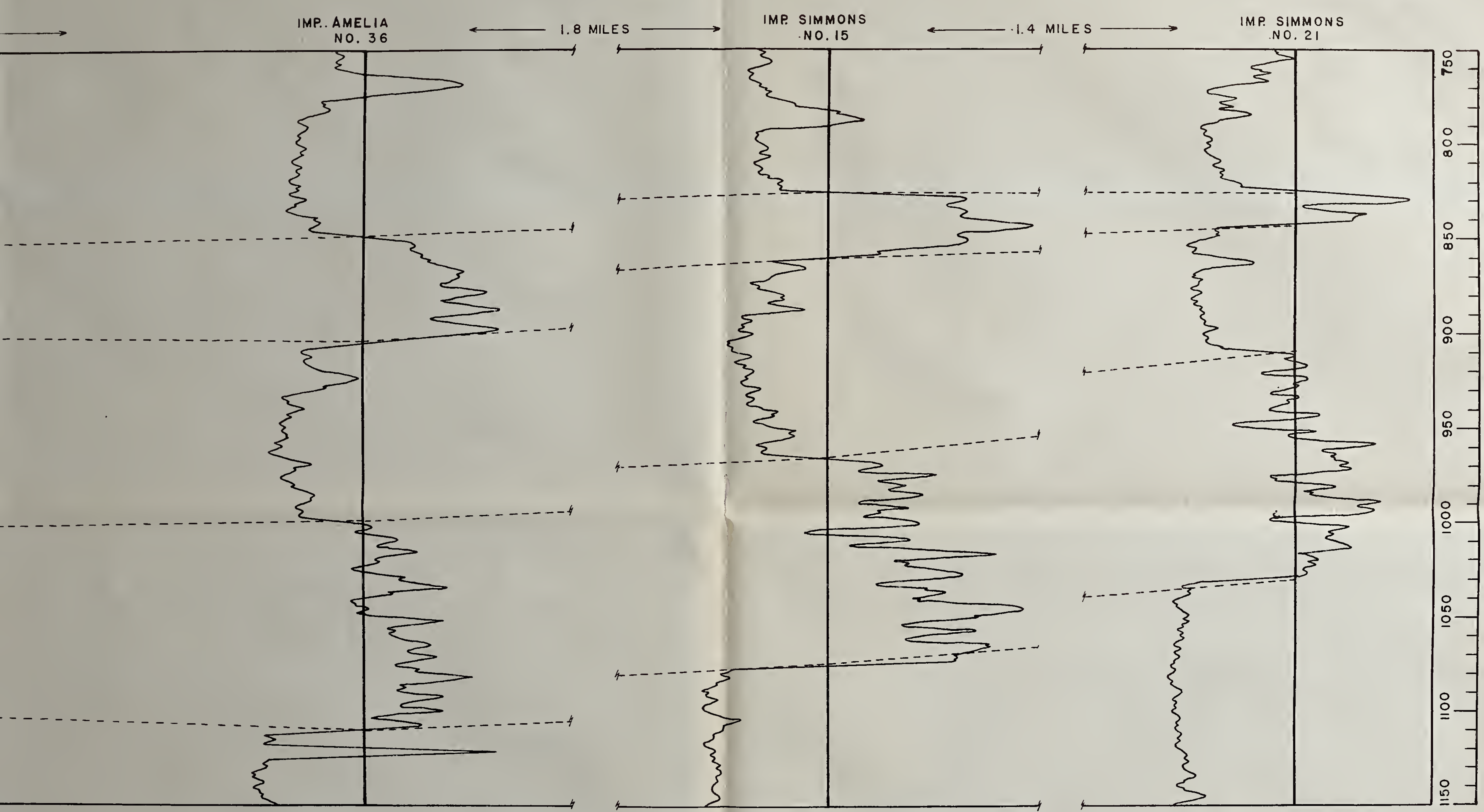
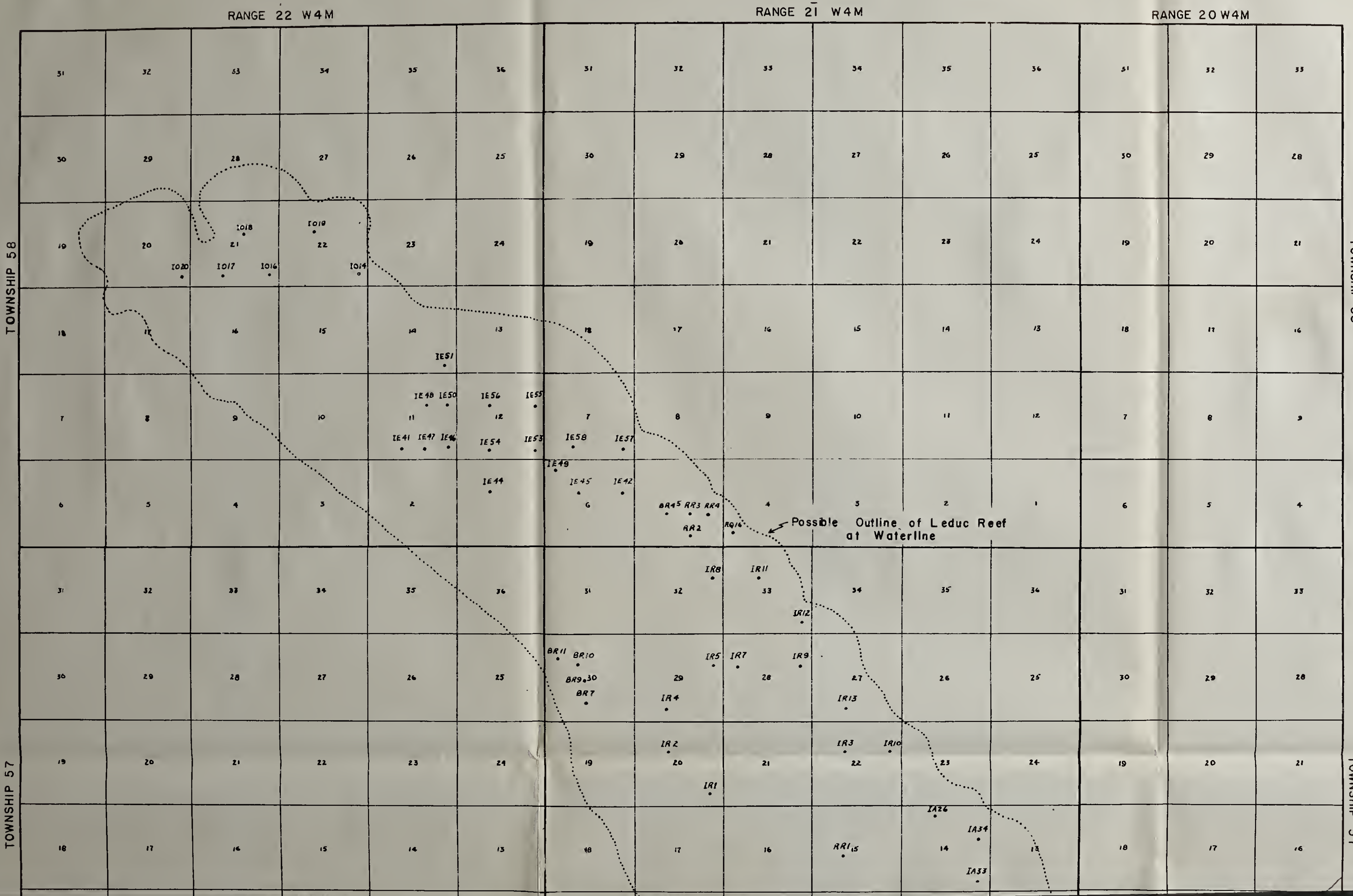


S.E.
IMP. AMELIA NO. 36
1.8 MILES
IMP. SIMMONS NO. 15
1.4 MILES
IMP. SIMMONS NO. 21
750
800
850
900
950
1000
1050
1100
1150

REDWATER


RANGE 22 W4M
RANGE 21 W4M
RANGE 20 W4M
TOWNSHIP 58
TOWNSHIP 57
Possible Outline of Leduc Reef at Waterline

INDEX MAP

SHOWING

LOCATIONS AND REFERENCE NUMBERS OF REDWATER WELLS

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